Appendix D. Groundwater Data and Methods

Contents

Overview

A groundwater analysis was conducted to investigate the potential for impact of the Gold King Mine (GKM) surface water release on downstream floodplain water supply wells. The accidental release of about 3 million gallons of acid mine drainage to Cement Creek above Silverton, Colorado, on August 5, 2015, resulted in a plume of dissolved and colloidal metals that flowed down stream to enter the Animas River near Silverton, Colorado, and joined with the San Juan River in New Mexico, continuing on through Utah before reaching the Lake Powell reservoir around August 12. At any point of the river the measurable dissolved plume flowed past within 48 hours. The legacy of deposited colloidal and particulate remained in the bed sediment. There are hundreds of active pumping wells located in the floodplain deposits of these rivers, including community wells, and private irrigation and household wells. This investigation was limited to the wells in the Animas River floodplain of Colorado and New Mexico. See **Figure D-1**.

The definitive question we address is: "Could drinking water or irrigation wells drawing from river alluvium become impacted from the chemicals associated with the GKM release?" (USEPA, 2016, pg. 70).

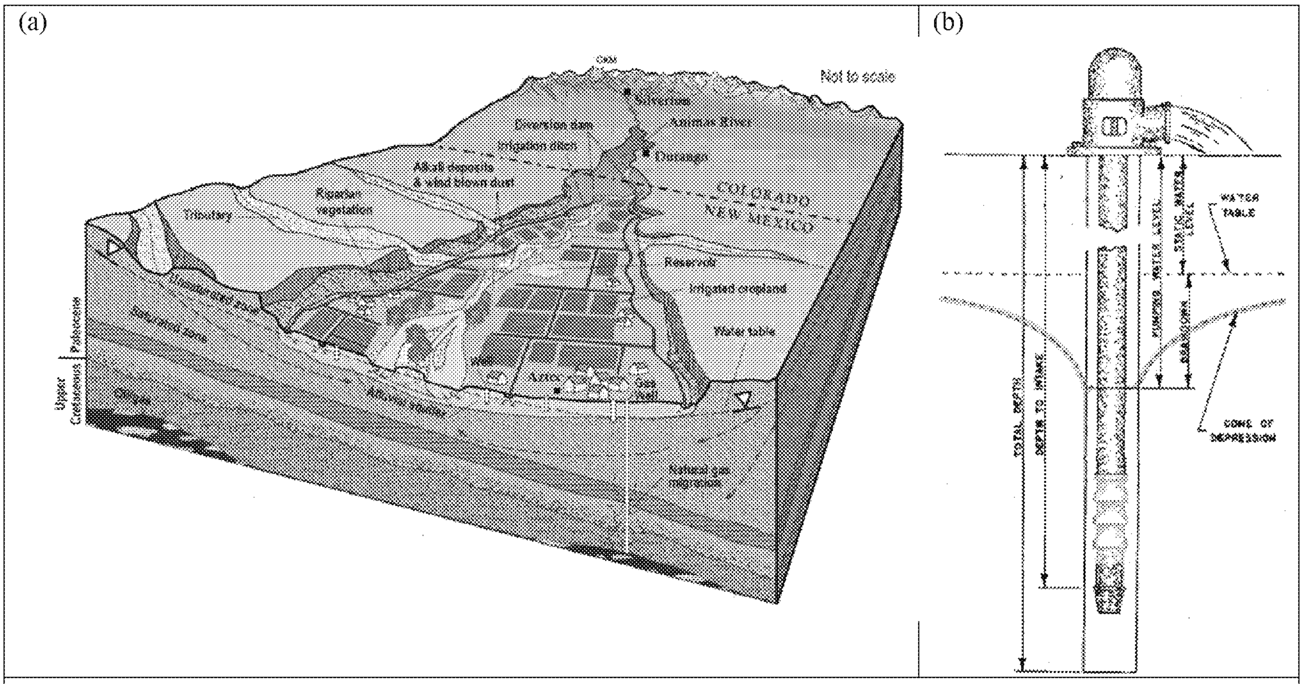


Figure D-1. A conceptual graphic of the floodplain aquifer of the Animas River and presence of water supply wells and irrigation ditches. (a) The groundwater flow lines indicate that on a regional basis the river is gaining water from groundwater, but on a local basis, perhaps under the influence of pumping wells, the reach may switch to a losing condition. The New Mexico Bureau of Geology and Mineral Resources has a dedicated aquifer monitoring program. A synoptic survey of river and well water levels was conducted in August 2015, and January and March of 2016. After Timmons et al. (2016). (b) A zoom-in engineering drawing of a typical community water supply well, showing influence of pumping from the screened interval on the water table resulting in a local cone of depression. After WestWater Associates (2010).

This definitive question may be broken up into three interrelated questions:

a) Which wells, if any, receive some of their water from the river?
b) What are the travel times of water from the river to those wells?
c) What is the dilution in the well of possible contaminants received from the river?

Question [a] can be answered with capture zone analyses for the various wells. Question [b] can be answered by use of forward particle tracking starting at the river and ending in the well. Question [c] can be answered by tracing particles backward in time from the well, using a uniform distribution of particles around the well, and then comparing the number of path lines that reach the river to those that do not.

It is assumed that most of the time the Animas River is a gaining water from the surrounding groundwater aquifer as it flows from Silverton, Colorado to Farmington, New Mexico. Under this scenario dissolved contaminants present in the river flow would travel downstream and not enter subsurface groundwater and have an exposure pathway to the floodplain water supply wells.

It would surprise few to find out that a high pumping well screened in the shallow permeable alluvium and located adjacent to the river receives some of its water directly from the river, even if that stretch of river is understood to be a "gaining" reach, that is, the floodplain is draining groundwater to the river. But how far away would the well need to be to stop sourcing from river water? And at what pumping rate would the well not be able to locally reverse the regional groundwater gradient toward the river, and thus stop sourcing from river water? Are there scenarios in location and time where the Animas River loses water to the floodplain aquifer, and thus bring the exposure pathway into play? And what happens with well-to-groundwater interactions if the river reach is "losing" water to the aquifer? Would nearby low volume pumping wells be expected to receive river water? In all cases, what would be the expected dilution of the plume at the pumping well?

This Appendix details the data requirements and methodology for the capture zone analysis and particle tracking. First, the foundations of the geology for the study region are described, including the nature of the flood plain deposits that make up the alluvial aquifer of the Animas River. Second, a discussion is presented about the basis for computational model selection and the approach taken for this study. Finally, the results of the capture zone and particle tracking investigations for the lower and mid Animas River water supply wells are presented.

Was there any empirical evidence of river-to-well communication and possible GKM plume capture? A community pumping well located in the mid Animas River floodplain and only 35m from the river had observed dissolved metals signals that had the characteristics of a breakthrough of a river plume moving through the aquifer to the well within a plausible time window. The signal was not definitive since there were other dissolved metals that did not indicate a breakthrough. Put it this way --- the hypothesis that this well experienced a river-to-well plume could not be rejected. Note the raw well water concentrations of the dissolved metals (pre-treatment and distribution) were significantly below human health advisory levels. The situation is discussed in detail at the end of this Appendix.

As a disclaimer --- this study was limited to an investigation of the <u>potential</u> for impact; an investigation of the <u>significance</u> of impact would require a more detailed human exposure and drinking water risk assessment. For example, only assessment of raw well water was considered, and not the water quality post treatment and distribution. The analysis was limited to publically available data; no site specific data was collected by the EPA Athens Animas River Team. And the assessment was limited to the dissolved constituents of the GKM plume and did not consider the deposited metals in the sediment as a potential long term source.

Background: Groundwater-surface water interactions in the Animas River floodplain deposits

The Animas River of Colorado and New Mexico is in dynamic communication with the permeable floodplain deposits, which contains a shallow aquifer that in some locations supports public community wells and private irrigation and household wells, amongst other water uses. The aquifers of interest are the "ribbon" floodplain deposits of the Animas River as it moves through the igneous/metamorphic rocks of the upper watershed, the sedimentary/sandstone dominated mid area, and the shale dominated lower area. See **Figure D-2**. The different geology has influence on the floodplain geomorphology and the shallow groundwater quality.

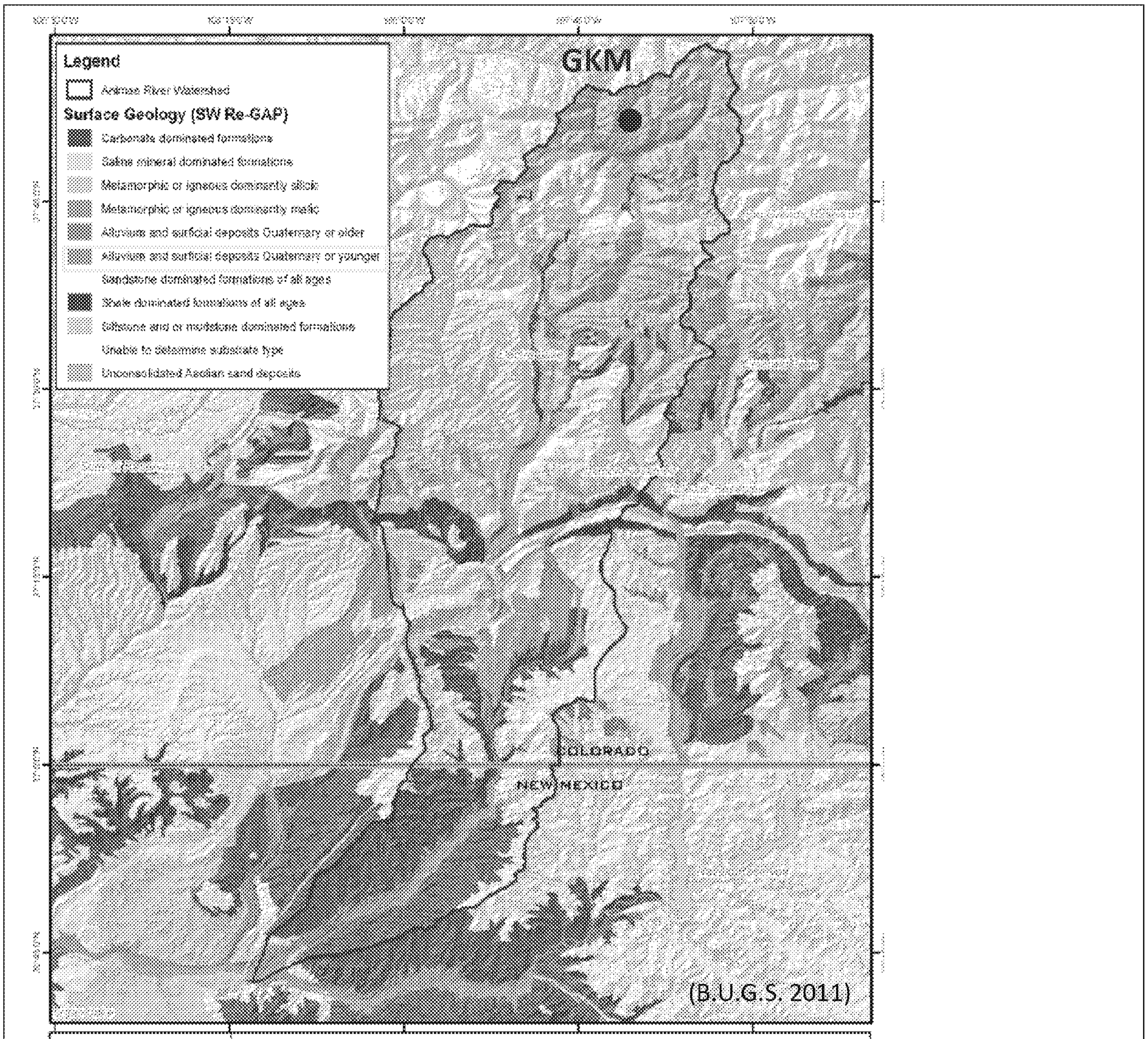


Figure D-2. Surficial geology of the Animas River watershed. The aqua blue designates the alluvial floodplain deposits. (B.U.G.S, 2011). Gold King Mine is in the far northern headwaters of the watershed. Broadly, the Animas River runs over three distinct geology zones: (1) the upper Animas and igneous/metamorphic rocks; (2) the mid Animas and the sandstones; and (3) the lower Animas and the shales. These distinct geology zones have influence on stream geomorphology and floodplain deposit water quality.

The Animas River floodplain of Colorado and New Mexico and the aquifer beneath is tapped by a large number of water supply wells and irrigation ditches. While the river is predominately a gaining stream on a regional basis, there are some times and locations where a river reach may be losing water to the shallow groundwater system (Timmons et al., 2016). We will examine multiple lines of evidence for groundwater-surface water interactions, including a water flow balance investigation, and a high resolution water elevation investigation.

A water flow balance investigation for the upper Animas River

The Animas River discharge reflects the annual cycle of late spring to early summer snowmelt runoff, with subsequent decreases in discharge, interrupted by infrequent rain events. This is demonstrated for the upper Animas River near Silverton, Colorado, see **Figures D-3** and **D-4(a)**. The cluster of USGS streamflow gages about Silverton allows a flow balance analysis to be conducted:

$$Q_{A@S} + Q_{C@S} + Q_{M@S} + Q_{GW} = Q_{AbS} \quad (1)$$

or

$$Q_{GW} = Q_{AbS} - Q_{A@S} - Q_{C@S} - Q_{M@S} \quad (2)$$

The difference between the sum of the cumulative stream flows and the measured streamflow is inferred to be made up of contributing diffuse groundwater inflow (Q_{GW}) along the Animas River between the upgradient and downgradient stations. The analysis suggests that for this river section that diffuse groundwater contribution is on the order of 10% of river streamflow. The Animas River around Silverton is understood to be a gaining stream most of the time, with groundwater draining toward the river, with some episodic exceptions during mid-summer, as shown in **Figure D-4(b)**. It is possible that late spring-early summer snowmelt has the potential to send a pulse of water to partially fill the alluvial aquifer.

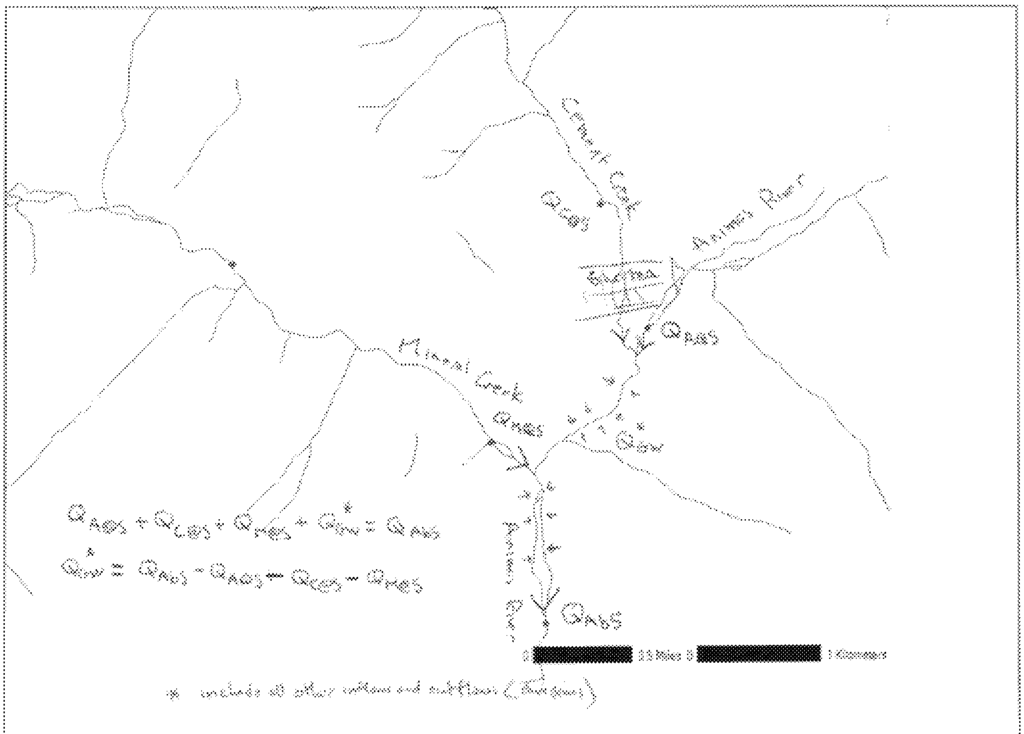


Figure D-3. Conceptual representation of the Upper Animas River discharges measured by the US Geological Survey and diffuse groundwater discharge near Silverton, Colorado. USGS gages include Animas River below Silverton (Q_{AbS}), Animas River at Silverton ($Q_{A@S}$), Cement Creek at Silverton ($Q_{C@S}$), Mineral Creek at Silverton ($Q_{M@S}$). The inferred averaged groundwater contribution to the outlet flow (Q_{GW}) includes diffuse subsurface flows and discrete spring flows as shown in red.

Church et al (2007, Chapter E9, pg. 488) applied a tracer-dilution method in the Cement Creek watershed and suggest that up to 21% of streamflow can be related to diffuse subsurface flow discharging to the stream; the rest comes from discrete mine effluent, springs, and tributaries.

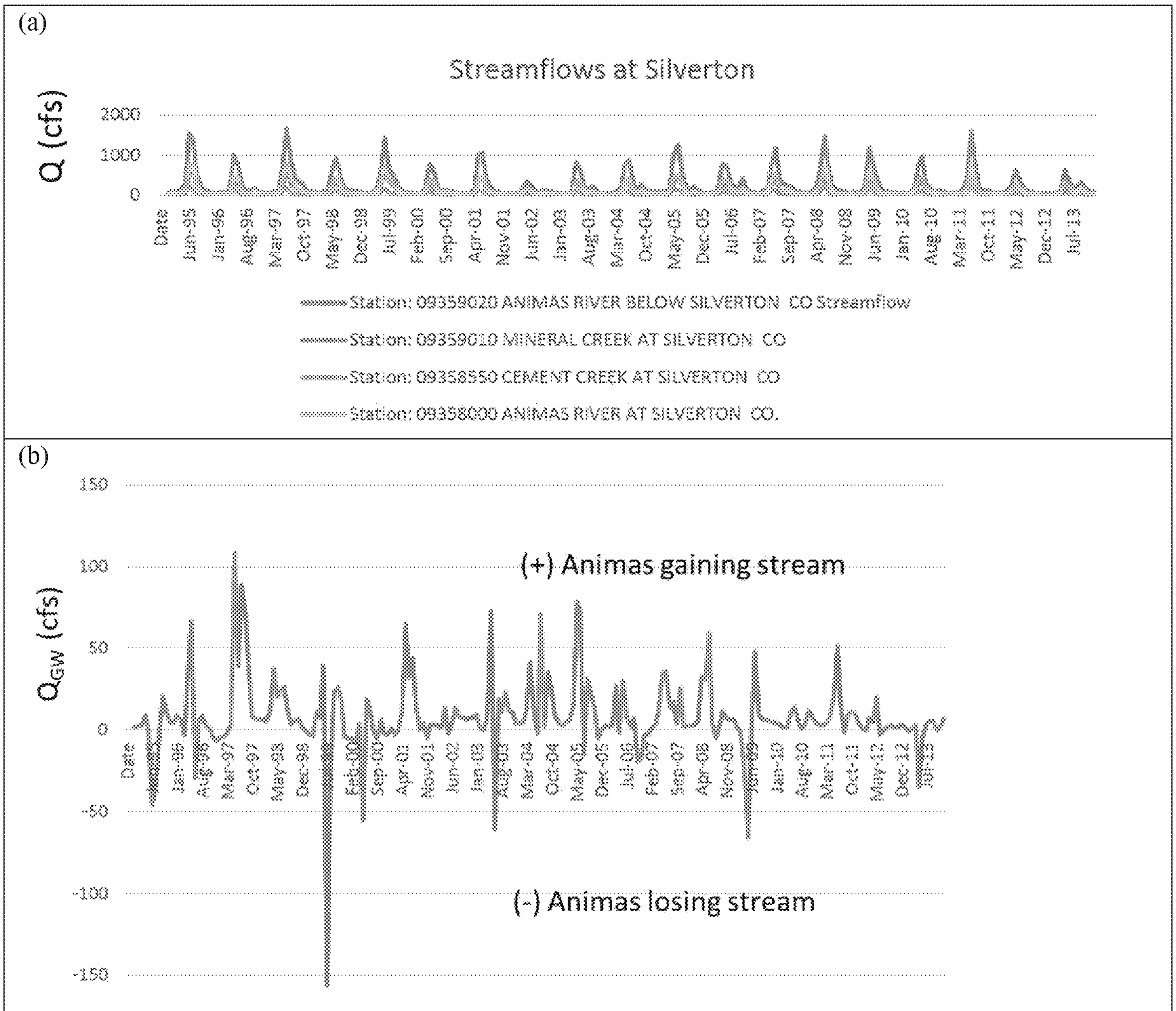


Figure D-4. Streamflow analysis of the upper Animas River near Silverton, Colorado. (a) Streamflow hydrograph of measured discharge in cubic feet per second (cfs) of the Animas River at Silverton, Colorado. (b) Inferred groundwater inflows along the section of the Animas River around Silverton, CO, 1995-2013. The positive inflow implies that the Animas River is gaining groundwater most of the time. The negative exceptions suggest the river losing flow to the alluvial groundwater system. Graphics from the USGS Groundwater Toolbox.

A high resolution water levels investigation for the lower Animas River

An investigation has begun of the potential for groundwater-surface water interactions in the lower Animas River between Riverside and Farmington, New Mexico. Timmons et al. (2016) of the New Mexico Bureau of Geology and Mining Resources (NMBGMR) are conducting a monitoring program supported by high resolution land surface elevation mapping using LiDAR data, verified (x,y) location of the sampled wells using hand-held GPS, and a synoptic surveying of well water levels. The January 2016 data represents the water table under "baseflow" conditions and not under the influence of mountain snowmelt runoff or irrigation ditches. There are a number of wells indicating a negative gradient in this section of the lower Animas River between Riverside and Farmington, New Mexico. See **Figure D-5.** The negative hydraulic head gradient would suggest that in these sections the Animas River are losing water to the aquifer during the January time period. Most of the potential losing reaches are in the northern half of the study region. The sporadic spatial distribution of the potential losing reaches underscores the site specific nature of the phenomenon. The NMBGMR also monitored the August 2015 and March 2016 time periods.

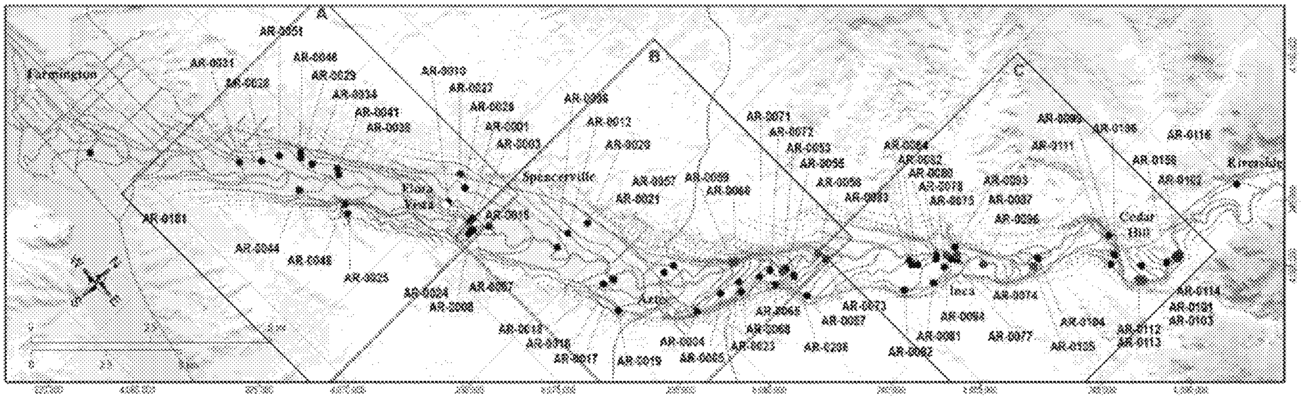
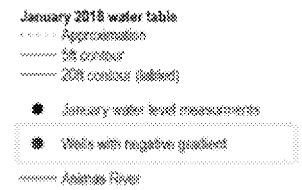


Figure D-5. High resolution survey of river and well water elevations in the lower Animas River. Based on high resolution synoptic mapping of well water levels and river water levels during “baseflow” conditions of January 2016. Hand-held GPS used for georeferencing well locations. LiDAR DEM used for estimation of land surface elevation. The wells with negative gradient shown in red. Note their more likely presence in the northern half of the study area, and the sporadic distribution.



Under the conditions where the Animas River is a gaining stream, a nearby pumping well would need to overcome the hydraulic head gradient in order to directly source river water, and if the river was transporting a plume of dissolved metals, establish a potential exposure pathway. The wells at risk would tend to be the community wells located in proximity to the river and that pump larger volumes of water. Under the conditions where the Animas River is a losing river, the hydraulic head gradient would potentially introduce dissolved solutes associated with a river plume into the groundwater aquifer, thus expanding the possible wells at risk to exposure to include nearby wells of lower pumping rates, such as the domestic or household wells. The groundwater modeling investigation was chosen to further the understanding of these potential exposure pathways for two areas: (1) mid Animas River; and (2) lower Animas River (**Figure D-6**) and described in the next section.

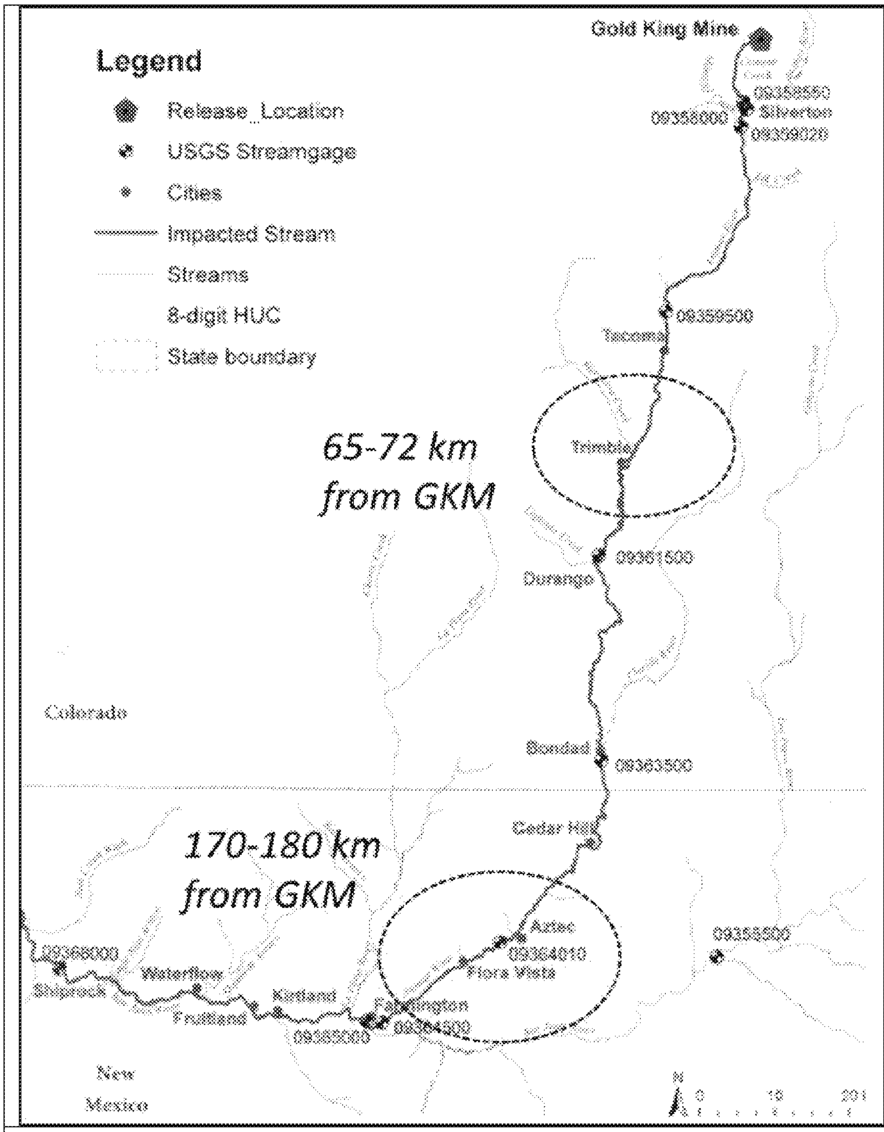


Figure D-6. The mid Animas and lower Animas River clusters of community and private wells selected for groundwater modeling analyses. (1) the mid Animas River area between Tacoma and Durango, Colorado, 65-72 km downstream of the Gold King mine release site; and (2) the lower Animas River area between Aztec and Farmington, New Mexico, 170-180 km downstream of GKM.

Groundwater Modeling Approach

The groundwater impact investigation used a step-wise and progressive computational modeling approach incorporating hand calculation, empirical and spreadsheet analyses, and mechanistic groundwater simulations using analytic element and finite difference methods.

Analytic element modeling is especially well-suited for the progression of simple to more complex representations of the geohydrologic system in order to test understanding. A suite of simple models with few measurable parameters is often preferred over a multi-parameter model that may better fit the data (Kelson et al. 2002). Simple models are used within a deterministic approach in our GKM investigation; a stochastic approach would require more field data than are available. The theoretical foundations of the analytic element method are documented in Strack and Haitjema (1981a, 1981b) and Strack (1989). The practical application of the analytic element method is covered in Haitjema (1995). A community of practice web page includes a survey of analytic element models (www.analyticelements.org).

While especially suitable for groundwater flow modeling at different scales, analytic element modeling does have some limitations. For instance, both transient flow and three-dimensional flow are only partially available. While an analytic element model can represent macro-scale heterogeneities (such as the difference in hydraulic conductivity associated with alluvium and hard-rock aquifers) in a piece-wise manner, the models do not currently represent gradually varying aquifer properties. The representation of multi-layer aquifer flow is an advanced analytic element technique.

Numerical methods for computational groundwater simulation, including finite element and finite difference methods, are better positioned for more complex conceptual model representation (e.g., transient flow, fully 3D flow, spatially discretized aquifer properties). In mathematics, finite-difference methods (FDM) are numerical methods for solving differential equations by approximating them with difference equations, in which finite differences approximate the derivatives. Derivatives in the partial differential equation are approximated by linear combinations of function values at grid points (https://en.wikipedia.org/wiki/Finite_difference_method).

What follows is a discussion of the specific analytic element and finite difference computational models selected for this study.

GFLOW

The analytic element computer program GFLOW (v.2.2.2) was used in this project to solve for regional and steady groundwater flow in single-layer aquifers (Haitjema 1995). GFLOW is well documented and accepted within the groundwater modeling community (Hunt 2006; Yager and Neville 2002), particularly when applied to shallow groundwater flow systems involving groundwater/surface water interactions (Johnson and Mifflin 2006; Juckem 2009) and for recharge estimation (Dripps et al. 2006). The mathematical foundation of the model includes equations that express the physics of steady advective groundwater flow within a continuum; continuity of flow and Darcy's law (water flows down the hydraulic potential gradient) are satisfied at the mathematical elementary volume.

GFLOW solves the regional steady-state groundwater flow equations using the analytic element method (Haitjema 1995; Strack 1989) based on the principle of superposition of elements—line-sink elements represent streams, point-sink elements represent wells, line-doublet polygon elements represent discontinuities of aquifer properties (such as hydraulic conductivity, base elevation, and no-flow boundaries), and area elements represent aquifer recharge. The model domain is unbounded making solutions flexible in scale, from regional to local, and vice versa. Boundary conditions corresponding with physical features are superimposed, putting more detailed representations in the nearfield and more course representations in the far-field. The separated influences of these elements on the regional flow field are shown in **Figure D-7**. GFLOW includes standard example run files to test proper model installation.

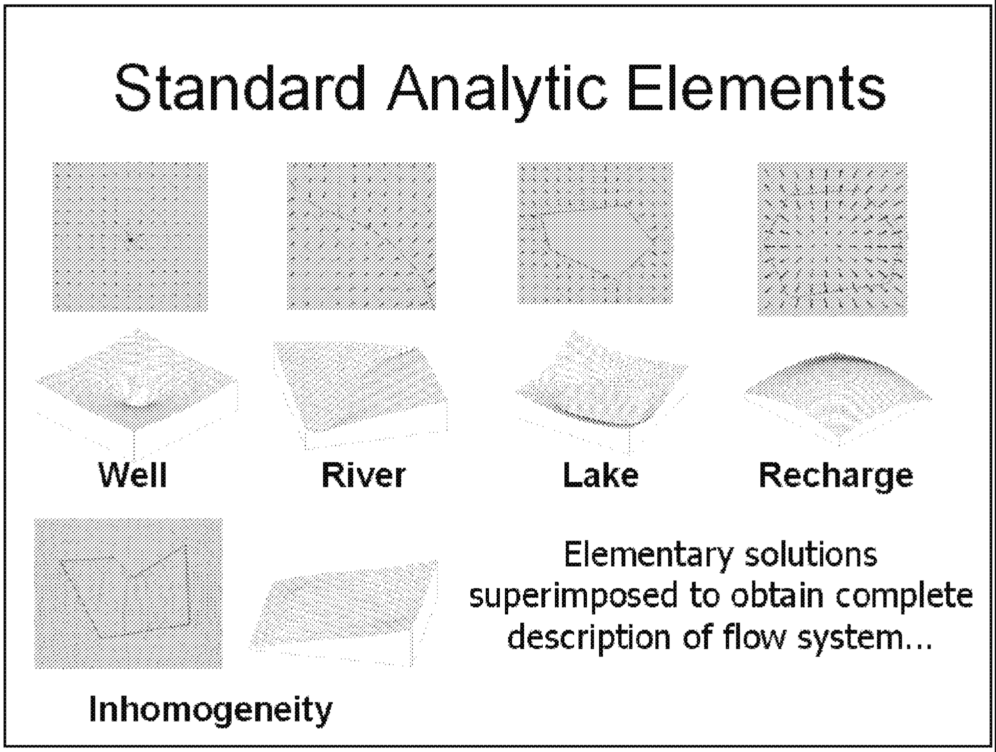


Figure D-7. Analytic elements: elementary mathematical points, lines, and polygons and associated landscape features. The suite of standard analytic elements available for superposition in the model domain to create a site specific model. The influence of the element on the hydraulic head contours and gridded water table surface and the velocity vectors is shown (Source: Craig 2014).

In practice, the basic steps for building a GFLOW groundwater flow model are to:

1. Collect data for model building and testing, including U.S. Geological Survey (USGS) stream gage data for baseflow characterization and static water levels in wells; USGS digital elevation maps (DEM) and digital raster graphic (DRG) topographic maps; and USGS digital line graph (DLG) maps of hydrography.

2. Build the model base map for hydrography and geology. Assign labels of topographic elevation (with respect to the mean sea level datum) along stream reaches.

3. Create the elements using line-sink strings to represent streams, point elements for wells, and area element polygons for various aquifer properties (recharge, hydraulic conductivity, aquifer base).

4. Run the GFLOW model and conduct manual or automated calibration, minimizing residuals (model simulated water table elevations compared to observed elevations; model line-sink network cumulative baseflow to field observed baseflow at the watershed outlet).

5. Refine the local scale, adding wellfields and conducting drawdown analyses and source water zone mapping.

The areas of interest for GFLOW models in this project ranged in scale from full "groundwatershed" aligned with the surface watershed down to an individual groundwater depot (e.g., pumping wellfield). Theoretically, analytic element solutions are spatially infinite, and good modeling practice typically represents both a far field, with coarse representation of elements and geohydrologic features, and a near field at higher resolution.

In GFLOW, to create a bounded flow solution assigned to a topographically defined surface watershed, a closed string of no-flow line elements are placed on the perimeter of the surface watershed. Even though the static no-flow boundary is an artificial one (not actually occurring in the natural system), the setup is justified in geohydrologic systems where the shape of the shallow water table tends to follow the shape of the surface topography, permitting the assumption that groundwater fluxes in and out of this boundary are insignificant. Also, the base of the single-layer aquifers are assumed to be horizontal and to constitute a no-flow boundary—indeed, it is assumed that deep leakage is minimal. GFLOW can represent flow in the aquifer as either unconfined or confined, or both. The bounded solution setup simplifies the calibration of a water balance associated with a surface watershed in the mountain terrain.

Shallow groundwater flow systems are intimately linked with surface drainage. The perennial stream network is understood to be flowing year round. In contrast, the ephemeral stream network is dry most of the year, only flows during intense rainfall events, and contributes to rapid surface runoff. The intermittent stream network is understood to be supported by shallow drainage of the unsaturated soil horizon. For a stream to be flowing when it has not rained for many days, the source of the river water is subsurface groundwater drainage, also called baseflow. The distinction on the landscape of perennial, intermittent, and ephemeral flow is dynamic and dependent on antecedent soil moisture conditions.

Field evidence of a snapshot of the topographically defined drainage network, including ephemeral, intermittent, and perennial channels, appears on USGS topographic maps (the dashed lines are assigned to intermittent channels, the solid blue lines to perennial channels). For the maps in our study area, and based on Google Earth “field reconnaissance”, the “blue lines” were expected to give a reasonable first estimate of the perennial stream network. The perennial stream network was used as a calibration target in the GFLOW model. Granted, the transition point on the landscape will move up and down the stream segment depending on groundwater recharge and the movement up and down of the shallow aquifer water table, the USGS blue line is hypothesized to be an effective representation of average drainage conditions.

The perennial stream network defines an internal boundary condition for GFLOW, and the network of line-sinks integrates and routes drainage from recharge to baseflow discharge at the groundwatershed outlet (Mitchell-Bruker and Haitjema 1996). The nominated stream locations from USGS topographic maps or digital elevation models (DEM) were translated into GFLOW line-sink representations of streams. Head at a location on the landscape is understood to be the elevation at which water saturates an open pipe piezometer driven into the aquifer. The strength (or inflow/outflow per unit length) of the line-sink is determined in the analytic element solution by maintaining a specified head in the center of the line-sink element. A combination of methods was used to estimate the land surface elevation at select locations on the GFLOW base map: (1) labeling elevations where elevation contour lines from the USGS map crossed the stream channel; and/or (2) labeling elevations at selected points on the landscape using a LidAR high resolution DEM. The GFLOW line-sinks were then manually superimposed on the base map, ensuring that vertices at the end of line-sink strings corresponded with points of known head/elevation from the USGS sources. The head at the center of each of the line-sink strings is calculated through linear interpolation.

The GFLOW conjunctive groundwater–surface water solution integrates the baseflow in the network of tributary streams represented by line-sinks to the watershed outlet, and through numerical iteration results in a flow solution that defines an active line-sink network. Headwater line-sinks that appeared above the water table in the model were allowed to dry up. The GFLOW recharge parameter was adjusted and associated with the areal element (inhomogeneity) and the baseflow was summed in the activated line-sink network to match the inferred baseflow observed at the USGS stream gage at the watershed outlet. In the semi-arid climate of Colorado and New Mexico, rather than attempt a formal baseflow separation, the average streamflow is assumed to be representative of baseflow. If one assumes there is no deep groundwater leakage and no subsurface flux of groundwater across the watershed boundary, the average groundwater recharge rate for the time period can be translated as the volume of baseflow distributed over the watershed area.

Another output of the GFLOW regional groundwater model is a continuous surface representing piezometric head, or groundwater flow potential. This surface of heads is the same as the water table surface for unconfined aquifers such as in the Animas River alluvium. The water table solution depends on the aquifer recharge rate and the aquifer transmissivity (or hydraulic conductivity times aquifer thickness). Assuming a constant transmissivity, the higher the recharge rate, the higher the model-predicted elevation of the water table. Conversely, assuming a higher recharge rate, the higher the aquifer transmissivity, the lower the water table will be. Once the recharge rate is known after conducting baseflow analysis as described above, the model can be calibrated to "fit" the observed water table elevations at points by varying the aquifer transmissivity, and monitoring the model-predicted water table at monitoring wells where the water table elevation is measured.

In summary, the two calibration targets, baseflow at the watershed outlet and observed elevations of the water table in unconfined aquifers, allow for the parameterization of the average recharge and transmissivity of the regional steady state aquifer flow system equations in the GFLOW model.

GMS-MODFLOW

Sometimes conceptual complexity, particularly at the local scale, suggests numerical modeling techniques. The USGS MODFLOW model is the most widely used groundwater flow model in the world. MODFLOW uses the finite difference numerical solution technique, with grid-based rows and columns, cells, multi-layer aquifer, non-horizontal base elevations, hydraulic conductivity, porosity and storativity can vary by cell (Harbaugh 2005). See **Figure D-8**. MODFLOW has undergone 30 years of development and quality testing by USGS.

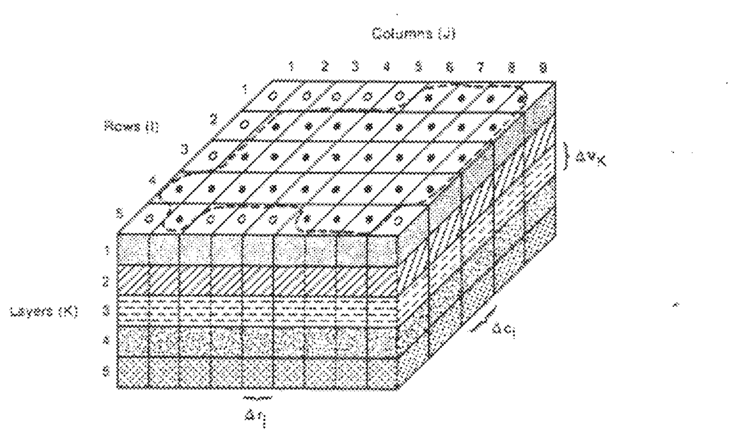


Figure D-8. The finite difference solution in MODFLOW solves for groundwater flow between cells as defined by rows, columns, and layers.

For this project, we used the MODFLOW-NWT and MODPATH (particle tracking) solvers within the Groundwater Modeling System (Aquaveo, GMS v 10.1). GMS includes standard MODFLOW example run files to confirm proper model installation. In addition to facilitating a standard cell-based interface to the MODFLOW finite difference grid, GMS includes a geohydrological conceptual design environment much like GFLOW.

Stepwise Progressive Approach

The stepwise and progressive groundwater modeling approach is not new (Sullivan et al., 2015, Appendix C; also http://www.haitjema.com). Ward and others applied what they called a telescopic mesh refinement computational groundwater modeling approach (TMR) to the Chem-Dyne hazardous waste site in southwestern Ohio (Ward et al. 1987). However, Ward et al. had to use three different finite differences numerical computer models for the three different scales at which they were modeling. Conditions on the grid boundary of the local scale were obtained from the regional-scale modeling results, while, similarly, the conditions on the grid boundary of the site scale were obtained from the local-scale modeling results. In contrast, the analytic element method for computational groundwater modeling allows these different scales to be treated within the same model by locally refining the input data, thus avoiding transfer of conditions along artificial boundaries from one model into the other. The step-wise progressive groundwater modeling approach taken for this study starts with analytic element modeling with GFLOW and progresses to finite difference modeling with MODFLOW as understanding and data justify.

The step-wise progressive groundwater modeling approach puts the emphasis on testing conceptual understanding, and less focus on site specific prediction. The modeling steps for this study included: (1) building the regional scale model including the far-field hydrogeologic boundary conditions; (2) testing the model performance with field observations of streamflow and water levels in wells as part of the calibration/harmonization process; (3) zooming down within the regional model to include local refinement of the conceptual model around the pumping well, such as aquifer heterogeneities, three-dimensional flow, transient responses; (4) another round of testing the model performance with field observations, such as pumping test data; and (5) repeat the modeling process by returning insights to the regional scale, and so on. Ideally, the modeling stops when the degree of hydrogeological and numerical complexity is sufficient that adding more detail does not change the answer to the study questions.

The GFLOW model was used for the initial regional scale and local scale modeling of steady state flow. The regional models provide initial boundary conditions for local scale transient and full 3D modeling using MODFLOW. See **Table D-1**. The implications of the various levels of complexity are discussed in the next sections.

Table D-1. Conceptual Complexity and Groundwater Model Selection

	Conceptual Complexity	GFLOW	MODFLOW
1.	Single Layer aquifer (piecewise homogeneous properties, horizontal base elevations, point sinks for wells, line-sinks for rivers, area elements for zoned recharge and aquifer properties)	☑	
2.	Dupuit Forchheimer assumption (neglect resistance to vertical flow; hydraulic heads constant with depth, horizontal 2D flow)	☑	
3.	Non-time variant (steady state) stress and flow	☑	
4.	Time-variant (transient) stress and flow		☑
5.	Three dimensional flow		☑
6.	Particle tracking (reverse – capture zones; forward – breakthrough response)	☑	☑

Dupuit-Forchheimer flow

The analytic element models used in this project fall in the class of codes that solve "two-dimensional flow in the horizontal plane," at least that is how these types of models are routinely referred to (USEPA, 2016, pg.71). This is misleading terminology. GFLOW is a *Dupuit-Forhheimer model*, which is a model in which resistance to vertical flow is being ignored, thus not vertical flow itself (Strack, 1984). While the underlying partial differential equation in GFLOW involves only the horizontal coordinates (x and y), flow into the vertical direction can and is being approximated using conservation of mass considerations. Consequently, path lines in GFLOW are being traced in three dimensions.

For a Dupuit-Forchheimer model to offer a good approximation to the actual three-dimensional flow regime, its application are more effective in groundwater flow systems in which the horizontal distances traveled by groundwater are much larger than the vertical distances traveled. In practice, this translates into groundwater flow systems in which the distances L between boundary conditions (e.g. distance of the well from the river) is larger than five times the aquifer thickness. This is for isotropic aquifers. In case the aquifer is anisotropic, with a lower vertical hydraulic conductivity than the horizontal conductivity, the following criterion may be used (Haitjema 2006):

$$L \geq 5H\sqrt{k_h/k_v} \tag{3}$$

Where H is the aquifer thickness, k_v is the vertical hydraulic conductivity, and k_h is the horizontal conductivity. For example, consider a well which is 35 meters from the river (horizontal) with a well screen that is about 25 meters below river. If Kh/Kv = 10 (ratios of 5 to 50 are common), the vertical distance in an equivalent isotropic medium would be about 80 m vertical distance (scale the vertical axis by the square root of Kh/Kv to make an equivalent isotropic medium). In this case, the vertical resistance between river and well screen would likely be greater than the horizontal resistance. Neglecting the vertical resistance in the GFLOW model overestimates the communication between well and river, and underestimates the travel time for flow from river to well (USEPA, 2016, pg. 81). The condition in the displayed formula above is not meant for wells that are relatively close to the Animas River, and unfortunately these are the wells of most interest (most likely to receive river water).

What is the consequence of violating the Dupuit-Forchheimer criterion for wells near the river? In reality the well - river interaction is influenced by possible (bottom) resistance to flow between the river and the aquifer, as well as resistance to vertical flow inside the aquifer. Neither is included in the model presented, although bottom resistance could have been applied. By not including any of these resistances, the flow potential for drawing water from the river that flows into the well is *overestimated*. In other words, the model as constructed *is conservative* with respect to the objectives of this study (USEPA, 2016, pg 81). Computer simulations of capture zones including full 3D flow from MODFLOW are compared to DF capture zones using GFLOW later in this Appendix.

Single homogeneous aquifer with horizontal base

GFLOW represents the alluvium near the Animas River as a single homogenous aquifer, which means that it lumps the various depositional layers in the alluvium into a single homogenous layer. Furthermore, it assumes a horizontal aquifer base below which no flow is considered. The question is how these simplifications affect the modeling results. Specifically, what effect does this simplification have on the potential well-river interaction? (USEPA, 2016, pg. 73)

There is not much known about the alluvial aquifer in terms of spatial heterogeneity and depth. The actual aquifer base at a specific location is unknown, but a geophysical survey gives some insight.

The Animas Water Company invested in a geophysical/gravimetric survey of the floodplain aquifer of the mid Animas River watershed near Hermosa, getting estimates of the base of the aquifer in five survey lines (or cross-sections). The permeable deposits are much deeper (600 to 1000 feet) than the current depth of the community wells in this area (about 100 feet). See **Figure D-9**.

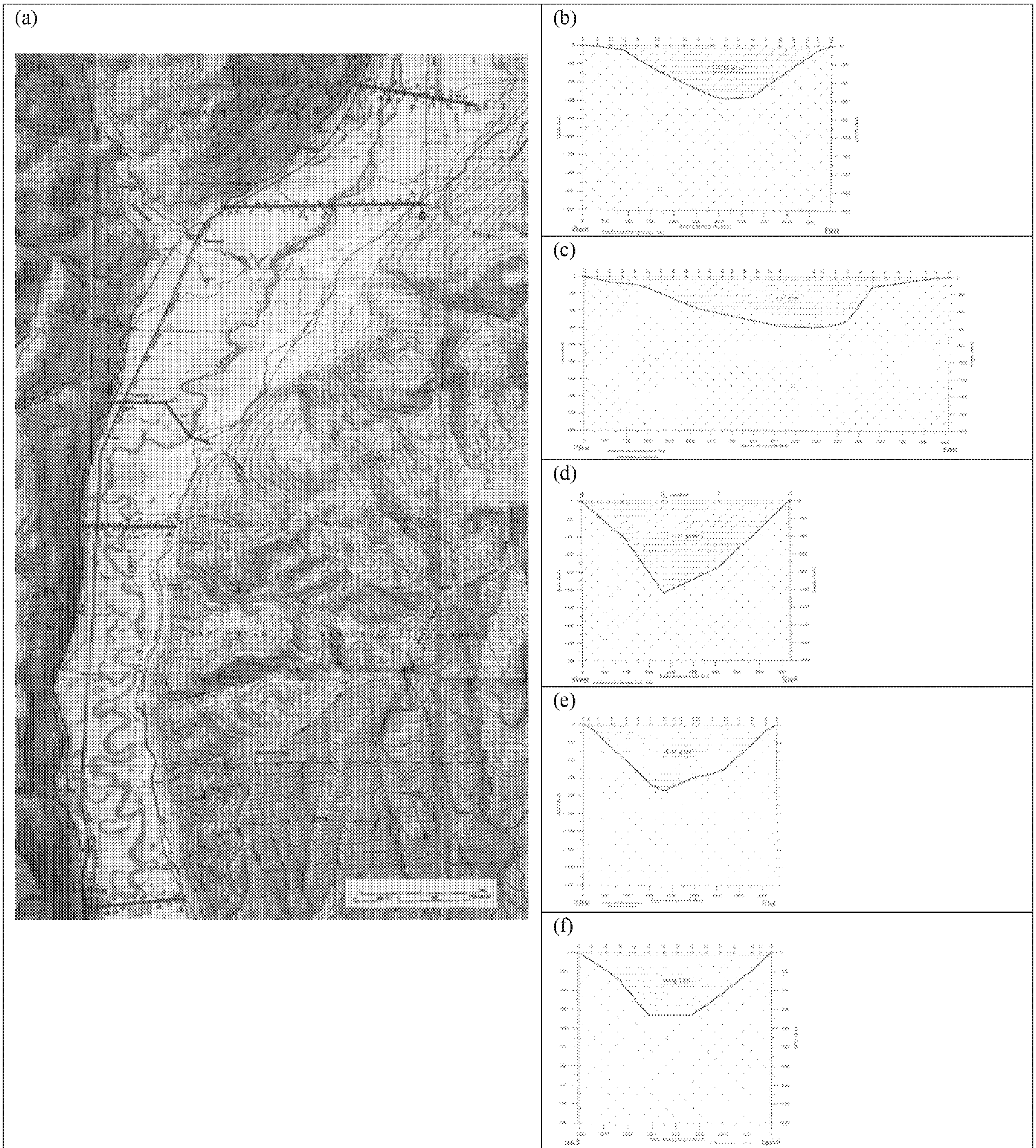


Figure D-9. Geophysics modeling of the shallow floodplain aquifer base elevation based on a gravity survey. (a) map of the five gravity survey lines; (b) line 1 gravity and depth profile – 2 layer model; (c) line 2; (d) line 5; (e) line 3; and (f) line 4. The model suggests the depth of the aquifer ranges from 600 ft to 1000 ft. Data source: Hasbrouk Geophyics, 2003.

The geophysical survey offered depths based on a two-layer model and three-layer model. The selection of the depths associated with the two-layer model most likely lead to an underestimation of the aquifer thickness. This is does not affect the flow regime much since the range of transmissivity in the model does not depend on this assumption because it has been constrained by pump test data. Assuming for a moment that the transmissivity is accurate (or reasonable), an underestimation of the aquifer thickness will result in an overestimation of the hydraulic conductivity, since the product of the two is the (known) transmissivity. So while the discharge rates in the aquifer, including the flow component from the river if present, are not affected (recall question [a]), the *specific discharges* and associated average groundwater flow *velocities* are. An underestimation of the aquifer thickness will result in an underestimation of the groundwater travel times (question [b]). This is *conservative* in view of the model objective since actual early arrival of contaminants may be later than predicted by the model.

The actual aquifer heterogeneity offers the potential for preferential pathways from the river to the well. The US Geological Survey (USGS) conducted a detailed study in the upper Animas River watershed near Eureka, Colorado, and a trench study revealed some of the complexity of the stratigraphy and gravel deposits. See **Figure D-10**.

The GFLOW model assumes a homogeneous aquifer that lacks preferential flow. Consequently, the assumption of homogeneity is **not** conservative in view of the model objectives. Preferential pathways would shorten the travel times from the river to the well (question [b]). While a multi-layer model may be able to capture this effect to some degree, such as AnAqSim (www.fittsgeosolutions.com), data on aquifer stratification near the study wells or between the wells and the river are absent.

(a)

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(b)

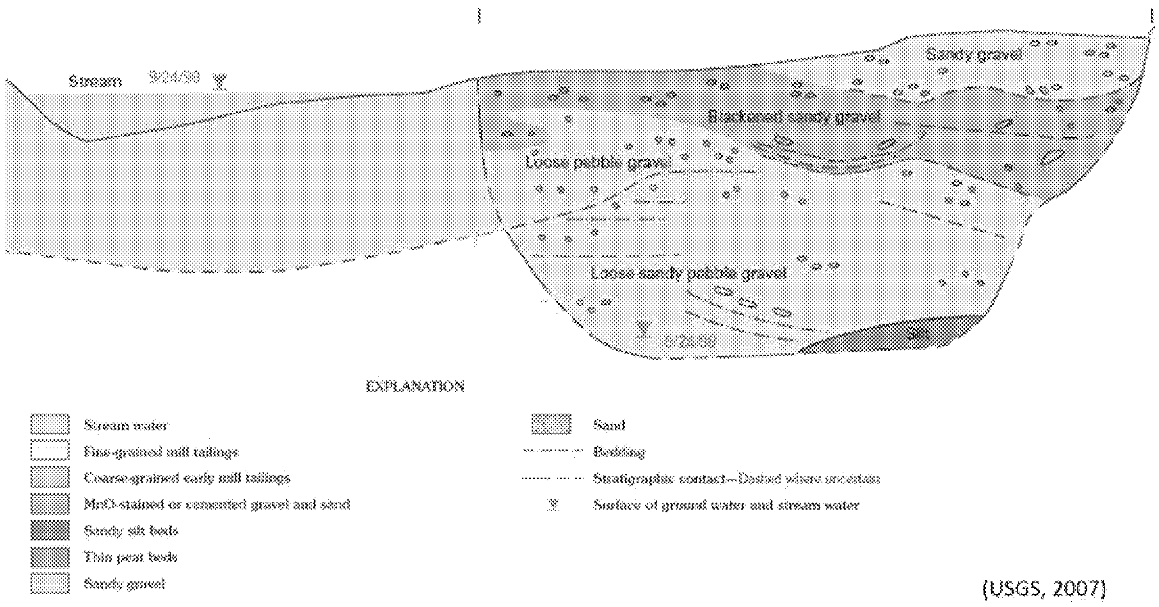


Figure D-10. Animas River in floodplain near Eureka above Silverton, Colorado. (a) Google Earth image showing the braided dry channels and the location of the geologic cross section. (b) Generalized geologic cross section of the shallow floodplain deposits of the Animas River above Silverton (Vincent, Elliott, 2007). The shallow stratifications include pebble and sandy gravels.

Preferential flow may well outweigh the effect of the aquifer thickness on the groundwater velocities. This will enter into the discussions regarding the empirical evidence of river-to-well communication at the end of this appendix.

Steady-state flow

GFLOW simulates steady state flow, ignoring water that may go into storage or is released from storage due to temporal changes in the water table (unconfined flow) or head (confined flow). For the purpose of capture zone delineation (in the context of wellhead protection), a steady state model is considered adequate (USEPA, 2016, pg 75). In fact, producing capture zones that change over time seems impractical for the purpose of managing wellhead protection areas. However, replacing the actual transient flow system by a steady state one raises the question what the steady state model actually represents. Haitjema (1995, 2006), using a study by Townley (1995), presents a dimensionless response time, τ:

$$\tau = \frac{SL^2}{4TP} \quad (4)$$

where S [-] is the aquifer storage coefficient, L [m] the distance between head specified boundaries, T [m^2/day] the aquifer transmissivity (product of aquifer thickness and hydraulic conductivity), and P [days] the period of a periodic forcing function. This formula differs slightly from the one presented on slide 12 due to a different definition of the distance L. When considering seasonal variations in flow in the alluvial aquifer, the definition of L on slide 12 is more convenient where it is the distance between the river and the valley boundary (rock outcrop). Haitjema (2006) offers the following rules of thumb:

$\tau < 0.1$ treat transient flow in the aquifer as successive steady state.

$0.1 \le \tau \le 1$ transient flow cannot be meaningfully represented by a steady state model.

$\tau > 1$ represent transient flow by a steady state model using average boundary conditions.

These guidelines are approximate in that values just below 0.1 or just above 1 are to be considered transitional from the aquifer responding relatively fast or slow to transient forcing, respectively.

A periodicity of P=365 days is appropriate to assess the response of the flow system to seasonal variations in recharge (in this case inflow into the aquifer near the rock outcrop) and seasonal variations in river stages; it is not suitable to assess the response of the flow system to short term variations in pumping and short term variations in river stage (e.g. storm surges). For that purpose a periodicity P=1 day would be a better choice. This reduction in the value of P would further increase the value of τ indicating that the aquifer responds rather slowly to storm events and pumping variations. This will be explored in testing against mid Animas River data later in this appendix.

Groundwater levels and calibration

In this study the groundwater flow model GFLOW is being calibrated using observed potentiometric heads (confined flow rock areas) or water table elevations (unconfined flow alluvium). In addition, base flows in the Animas River are also included as calibration targets. Calibration leads to the determination of most likely hydrogeological parameters such as hydraulic conductivities, aquifer recharge due to precipitation, and perhaps stream bottom resistances (USEPA, 2016, pg. 78). In the Animas River of New Mexico high resolution synoptic surveys of static water levels were available. In the Animas River of Colorado we used the static water levels reported in well driller's logs.

Currently, hydraulic gradients toward the Animas River are generated in the model by defining head specified boundaries away from the river. The water released by these head-specified boundaries presumably comes from the surrounding mountains. A common approach in modeling flow in alluvial valleys is to apply so-called "mountain range recharge" along the valley boundaries at the bottom of the surrounding mountains. In GFLOW this could be done using discharge-specified line-sinks along the base of the mountains or boundary of the alluvium. Since there was not data to support the mountain range recharge, the contribution was estimated using observed baseflow increases along the Animas River.

Lower Animas River Groundwater Models

A pumping well located in proximity to the river has the possibility to reverse the background hydraulic gradient and capture water from the river, depending on proximity and pumping rates. Groundwater flow modeling was used to investigate pumping scenarios consistent with observed conditions. The lower Animas River regional groundwater modeling will be presented first because of the existence of a high resolution topographic data set (digital elevation model DEM) and a series of synoptic surveys of the well water levels and river water levels from August 2015 and into 2016.

Lower Animas River GFLOW Model Setup

The regional groundwater model solves the hydrological water balance between the USGS gages at Aztec and Farmington. The DEM is used to define the outer boundary of the catchment. See **Figure D-11.**

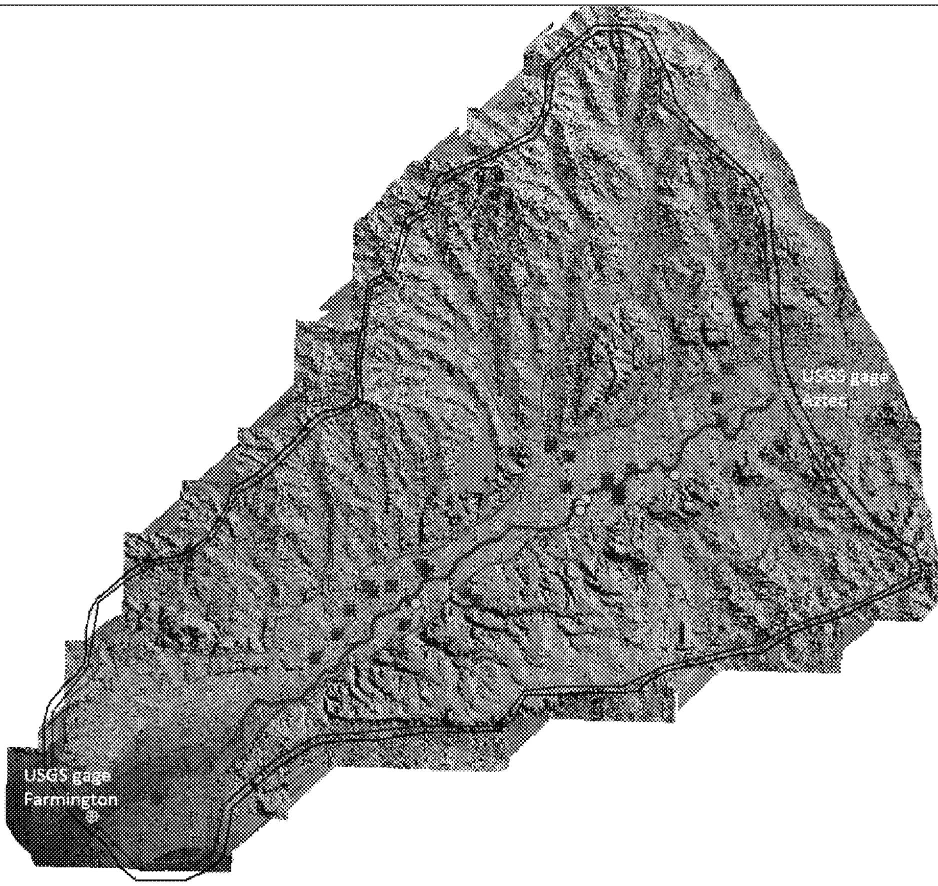


Figure D-11. Community wells (orange) and private wells (red) for the Lower Animas River floodplain study area. The catchment draining between the USGS gages at Aztec and Farmington was delineated as guided by the LiDAR DEM. Data source: New Mexico Resource Geographic Information System (http://rgis.unm.edu/)

The surficial geology of the lower Animas River watershed for the study region is mapped in **Figure D-12**.

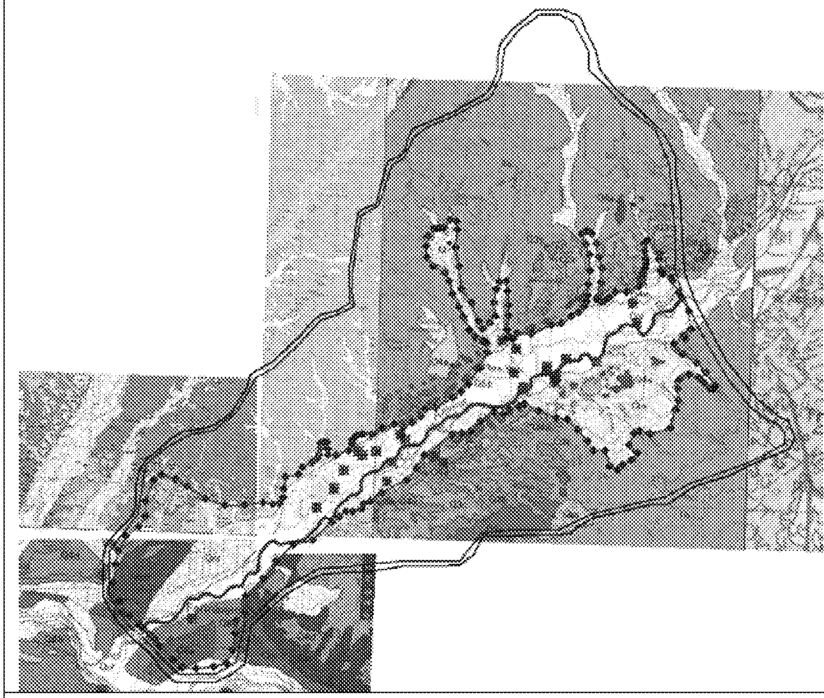


Figure D-12. Lower Animas River geology. The interpreted boundary of the alluvial aquifer is delineated. Data: USGS national geologic model database.

A sampling of community wells was extracted from the New Mexico Water Rights Reporting System (NMWRRS) for the Animas River floodplain between Aztez and Farmington (RK 170-180), and the data reported in **Table D-2**.

Table D-2. Lower Animas River floodplain, community well data, New Mexico

Identification*	Total depth (ft)	Static water level (ft bgs)	Pumped water elevation (ft bgs)	Well yield (gpm) observed, estimated	Average annual well diversion right (acre-ft)
76m174km	21	6	NA	150	62.9
21m174km	23	7	NA	150	62.9
101m174km	21	7	NA	150	62.9
90m179km	25	NA	NA	1,000	1,935
18m171km	NA	NA	NA	125	1.36
*An ID was assigned to the community wells incorporating distance from river (in meters) and downstream distance from GKM (in kilometers) in the name.					

The layout of analytic elements used in the GFLOW representation of the lower Animas River are shown in **Figure D-13**. The base of the single-layer aquifer is assumed to be horizontal and to constitute a no-flow boundary. The GFLOW model represents the outer boundary as a no-flow boundary, that is, no solution occurs outside of this boundary. GFLOW also uses a polygon to distribute area recharge over the catchment only. Another analytic element polygon encloses the floodplain alluvium and associates a higher hydraulic conductivity than the outer rock domain. The perennial stream network defines an internal boundary condition. The nominated stream locations from USGS topographic maps or digital elevation models (DEM) were translated into GFLOW line-sink representations of streams. Head at a location on the landscape is understood to be the elevation at which water saturates an open pipe piezometer driven into the aquifer. The strength (or inflow/outflow per unit length) of the line-sink is determined in the analytic element solution by maintaining a specified head in the center of the line-sink element. A combination of methods was used to estimate the land surface elevation at select locations on the base map: (1) labeling elevations where elevation contour lines from the USGS map crossed the stream channel; and/or (2) linear interpolation along the line-sink. The line-sinks were then manually superimposed on the base map, ensuring that vertices at the end of line-sink strings corresponded with points of known head/elevation from the USGS sources. The head at the center of each of the line-sink strings is calculated through linear interpolation. Wells are represented with point elements. A piece-wise representation of the hydraulic conductivity (k) property is achieved with the polygonal representation of the higher-k unconsolidated floodplain deposits.

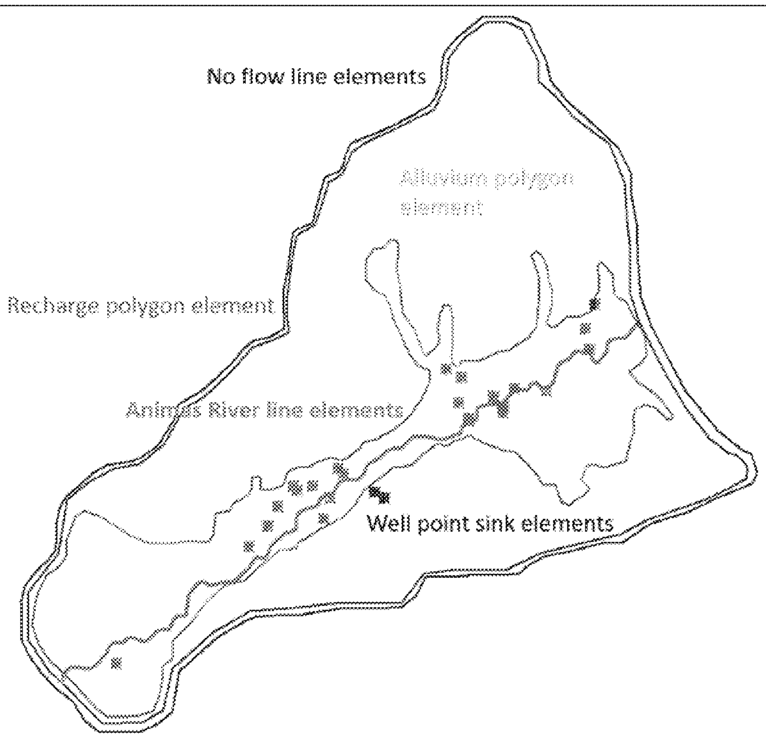


Figure D-13. Layout of GFLOW analytic elements for the Lower Animas model.

Lower Animas River GFLOW Model Calibration

The areal recharge was distributed over the catchment between the USGS gages in order to satisfy the water balance of August 2015. The observed stream flows are shown in **Table D-3.**

USGS gage data for Farmington was provisional at the time of analysis, so estimated based on historical observations at two gages

Table D- 3.

USGS Gage Name	USGS Gage Number	Discharge average 8/12-8/15/2016 (cfs)	Discharge on 1/14/2016 (cfs)	Discharge average August-October, 2015 (cfs)	Discharge average August-October, 2003-2015 (cfs)
Animas River below Aztec NM	09364010	~~603~~ 654.7	229	365	428
Animas River Farmington NM	09369500	~~633~~ 684.3	240 estimated*	360	438
*Qfarm/Qaztec = 1.049 based on 2003-2016 data for January.					

The NMBRMR conducted a synoptic survey of water levels in private wells during the period August 2015, January and March 2016 (Timmons et al., 2016). The also monitored continuous precipitation and Animas River and irrigation ditch stages at select locations. See **Figure D-14**. As would be expected, the Animas River stage elevation responds very quickly to precipitation events. The alluvial well in this location has a more muted and delayed response to the precipitation/river stage signal. About a 5 day delay in the signal from river stage to well response is expected based on observations at an alluvial well. Also, the influence of the irrigation ditches is apparent. Once the irrigation ditch is drained for the winter, the water levels in the alluvial well drop to the baseflow levels.

A significant observation is the sensitivity of aquifer water levels to the operation of the irrigation ditches which are important sources of water for the irrigated cropland in the growing season.

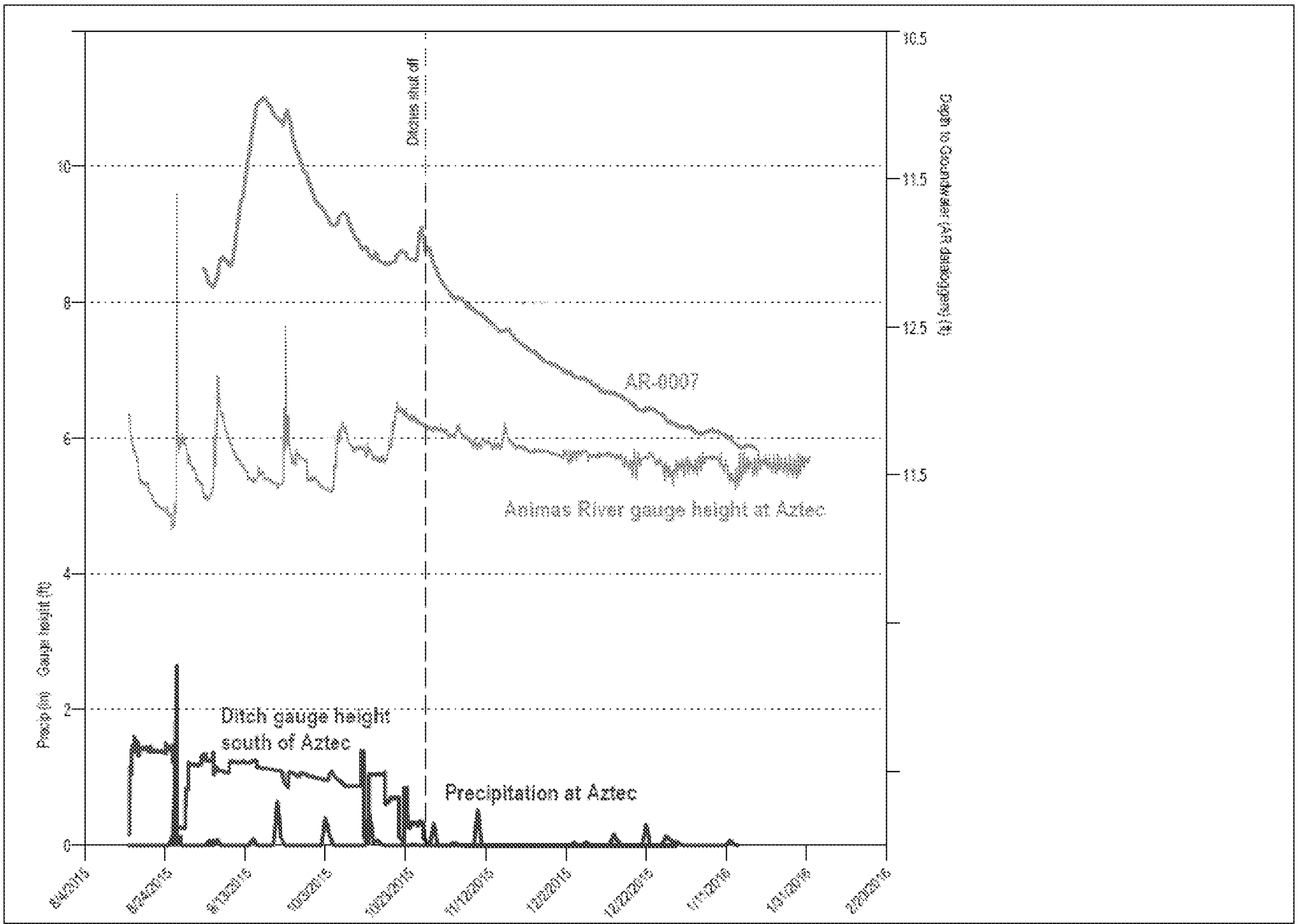


Figure D-14. Hydrographs from Aztec area including a well with continuous data recorder plotted with influences from precipitation and Animas River stage and ditch gage height. Well AR-0007 is located on the south side of Aztec, is 32 ft deep, and is located on the east side of the river. (modified from Timmons et al., 2016).

Scenario 1. GFLOW regional model for January 2016 hydrologic condition

The GFLOW model was calibrated first for areal recharge over the catchment area, and second for hydraulic conductivity of the rock and alluvium. The January 2016 period was used for calibration since during this baseflow period the irrigation ditches were not involved in the water balance --- start simple and add complexity. We used the synoptic survey of water levels conducted by Timmons et al. (2016). The regional recharge over the study area was calibrated to satisfy the regional water balance at the Farmington USGS gage. See **Figure D-15**. The net flow (input – output = change storage = zero), or $Q_{farm} = Q_{aztec} + N_{study\ area} * study\ area - Q_{wells}$. An average pumping rate for the private domestic water wells was assumed to be 400 gallons per day.

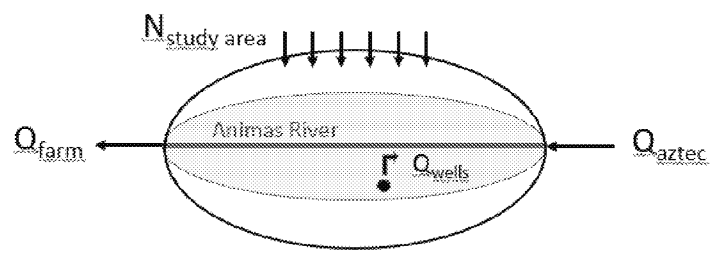
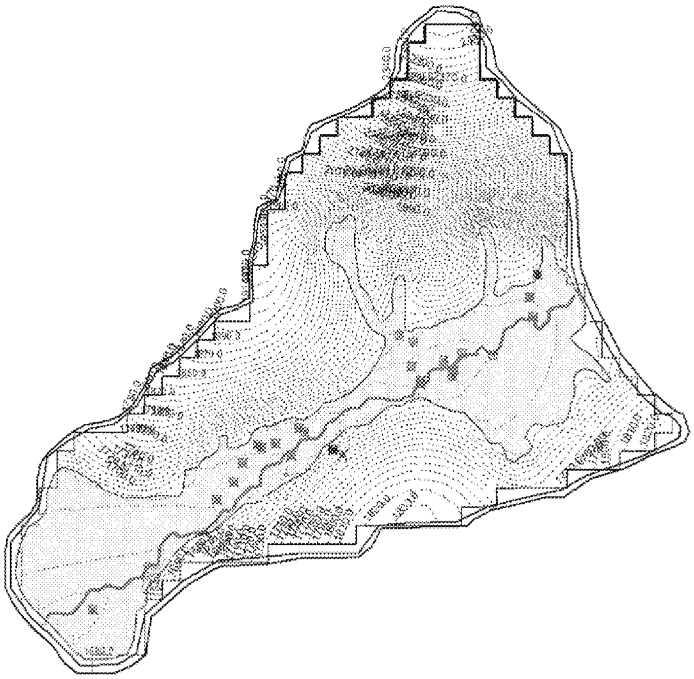


Figure D- 15. Conceptual diagram of water balance used in the GFLOW model for the lower Animas River without ditch diversions.

The GFLOW map of hydraulic head contours are shown in **Figure D-16 (a).** The resulting manual calibration of the rock hydraulic conductivity that minimized the residual error was k_rock = 0.035 m/d. The resulting calibration for alluvium hydraulic conductivity was k_alluv=2.2 m/d. The calibration statistics are shown in **Figure D-16 (b), (c).**

(a)



(b) alluvium test points

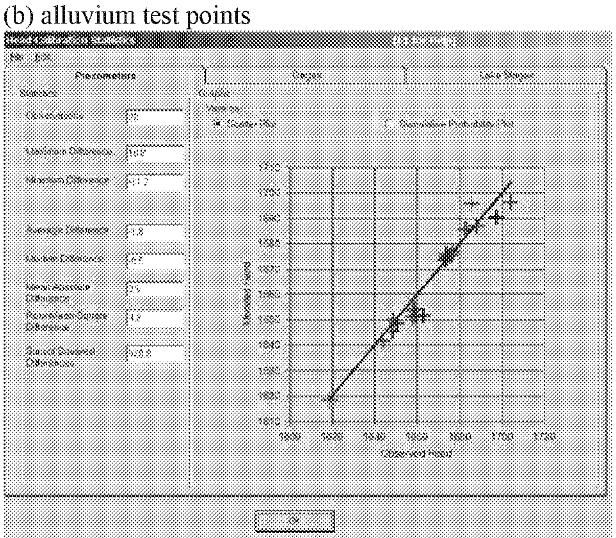


Figure D-16. GFLOW calibration for lower Animas River regional groundwater model for January 2016 flow conditions. The model areal recharge satisfying water balance was N =1.556E-4 m/d. Static water levels were measured at wells and entered into the GFLOW model as test points. Calibration minimizes the residual error or difference between the observed water levels and the model predicted water levels. (a) resulting calibrated model and regional hydraulic head contours; (b) calibration statistics for the test points located in the alluvium , alluvium hydraulic conductivity k_alluv=2.2 m/d and rock hydraulic conductivity k_rock = 0.035 m/d . Thus, at any specific alluvium well the model is on average low by 1.8 meters.

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Scenario 2. GFLOW regional model of the August 2015 hydrologic period

During the August 2015 period, the time of the GKM release and transport, the irrigation ditches would be expected to be in full operation. A GFLOW model was constructed to include the irrigation ditches as constant head linesinks. The location of the ditches is shown in **Figure D-17**. The elevation of the water levels in the ditches was estimated using the LiDAR DEM. The layout of linesink representation of the ditches in the GFLOW model is shown in **Figure D-18**.

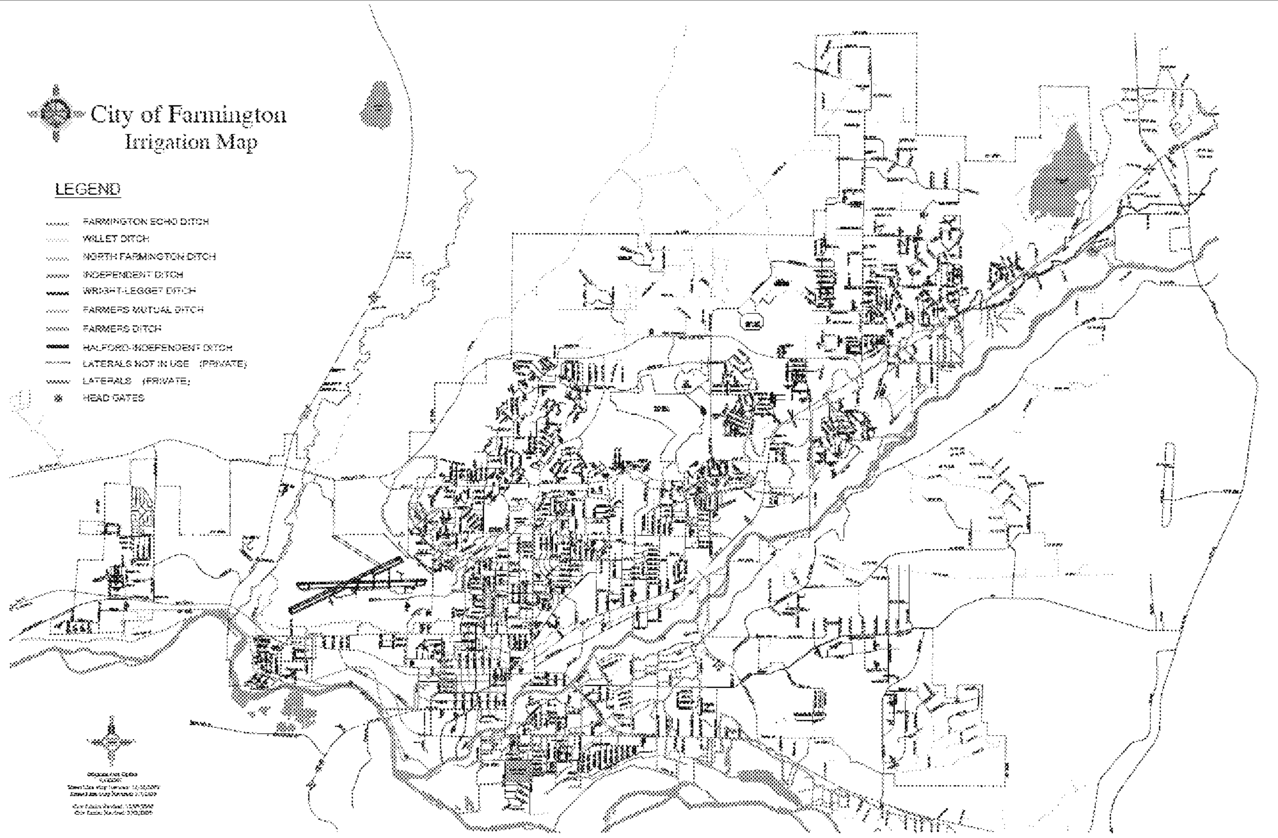

Figure D-17. City of Farmington, NM, irrigation ditch map. The streets are shown as black lines; the irrigation ditches are shown in colors (city map, updated 2009).

The NMBGMR provided a synoptic survey of private water well elevations for the dates, 8/17 – 8/20/2015. A 5-day delay from Animas River stage to well response is expected. Therefore, Animas River discharge was averaged for dates 8/12-8/15/2016, see **Table D-2**, for the water flows.

Figure D-18. GFLOW layout of elements including line-sink representation of irrigation ditches in the lower Animas River study area. The elevation of the water levels maintained by the ditches informed by the high resolution LiDAR elevation data.

The GFLOW solution that satisfies the steady water balance for the August 2015 time period, and which minimizes the residual error between model calculated hydraulic head and observed water levels in the water supply wells, is shown in **Figure D-19**.

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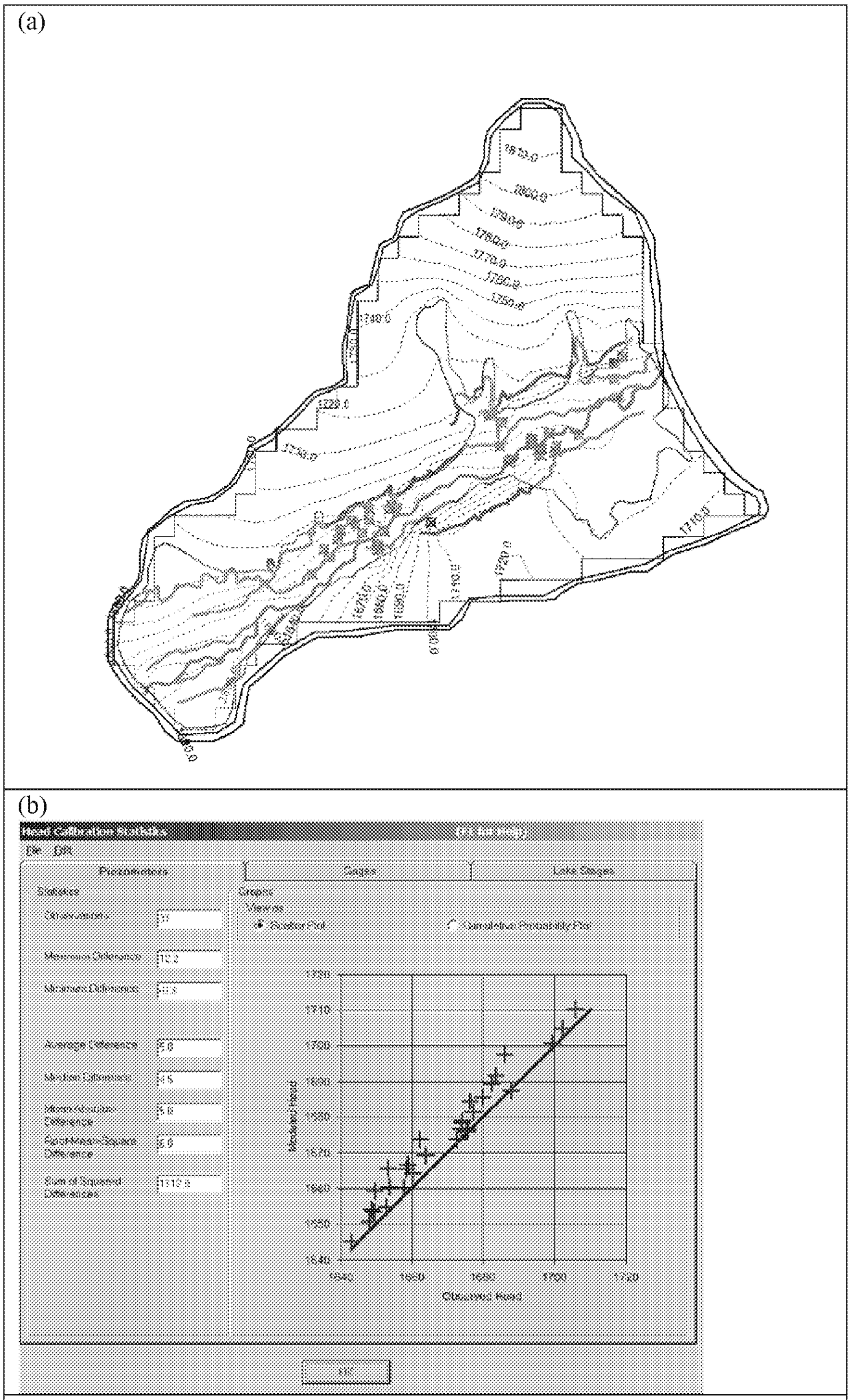
(a)



(b)

Figure D-19. GFLOW regional groundwater model lower Animas River for August 2015 time period, including irrigation ditches. The effective recharge over the catchment area N=0.215e-4 m/d (Qobs=1548682.3 m3/d, Qmodel = 1549688.0 m3/d, error = +5.70 m3/d)
Set k_rock=0.035m/d, k_alluv=2.2 m/d from previous calibration. The average head difference error went up to plus 5m.

Scenario 3. GFLOW regional model of the August-October 2015 hydrologic period

The water balance for the lower Animas River study area can be refined to include the observed major diversions from the Animas River to the irrigation ditches. This data is collected by the New Mexico Office of the State Engineer, Interstate Stream Commission, and publically available on the Real-Time Water Measurement Information System webpage (http://meas.ose.state.nm.us/). The sum of the diversions for the August to October 2015 time period is summarized in **Table D-4**.

Table D- 4. Irrigation ditch diversions (New Mexico Office of the State Engineer)

Ditch Name	Diversions Aug-Oct 2015 (m^3/d)
Kello-Blancett	21,166.3
Halford-Independent	40,105.1
Ranchmans-Terrell	7,358.2
Farmington Echo	69,476.7
North Farmington/Wright-Leggett	11,649.0
Sum total	149,755.3

The Scenario 2 GFLOW model was adjusted to represent the August-October 2015 water balance, including the influence of ditch diversion and pumping well extraction. With reference to the conceptual diagram of the water balance of **Figure D-20,** the study area Animas River inflows at Aztec, NM was estimated as the measured flow (from **Table D-2**, 428 cfs or 894,142.6 m3/d) minus the total diversions (149,755.3 m3/d) or Q_{aztec} = 744,387.3 m3/d. The observed average flow at Farmington, NM is Q_{farm} = 880,128.6 m3/d). The estimated pumping rates of the community wells (reported average diversions) and estimated pumping from the privates wells (400 gallons per day). The GFLOW manual calibration varied the recharge over the floodplain alluvium deposits until the residual error (model observed minus model simulated flow at the Farmington outlet, Q_{farm}) was minimized, resulting in model recharge over the alluvium N_{alluv} = 0.005 m/d.

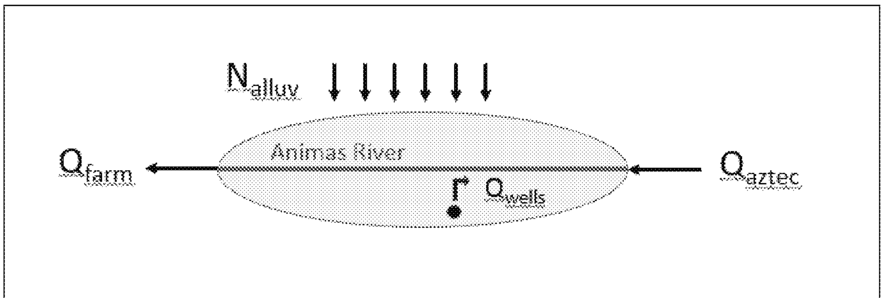


Figure D- 20. Conceptual diagram of water balance used in the GFLOW model for the lower Animas River including the influence of irrigation ditch diversions.

Local scale GFLOW model for a lower Animas River floodplain community well

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The calibrated regional GFLOW model for the averaged hydro period August-October 2015 provides the basis for the evaluation of floodplain water supply well sourcing from the lower Animas River, where an example community well (21m174km) is used to explore local scale capture zone delineation and solute breakthrough.

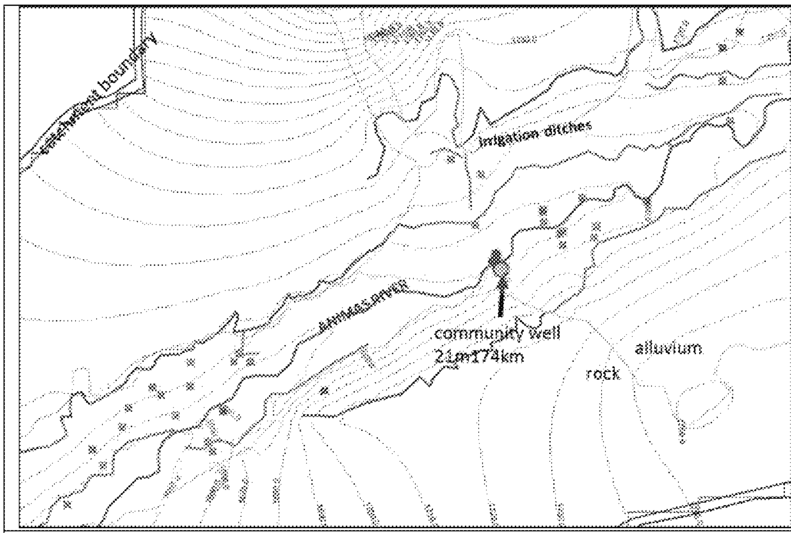
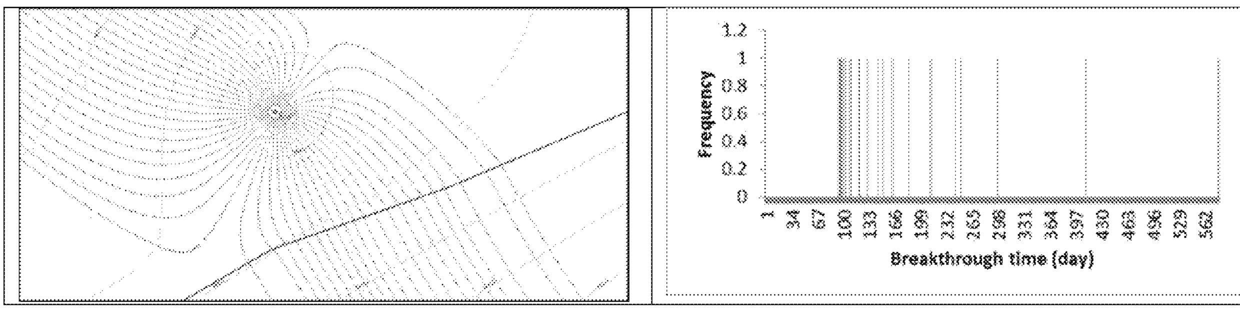


Figure 21. GFLOW model of groundwater-surface water interactions in the lower Animas River floodplain between Aztec and Farmington, New Mexico (RK 170-180) for the averaging period August – October 2015. Effective areal recharge accounting for the irrigation ditch return flow is 5.3E-3 m/d. Rock hydraulic conductivity is 0.035 m/d and alluvium hydraulic conductivity is 2.2 m/d. The river and irrigation ditches are represented as line-sinks. The private and community wells are represented as point sinks. The 90 day capture zones of the wells are too small to be seen at this scale. The model suggests only the 21m-174km community well pumping at a maximum rate of 817.6 m^3/d sources from the river.

While the GFLOW model predicted the 21m174km community well may source from the Animas River, the first arrival of the plume took over 90 days, and dilution was dominant. The aquifer would take almost 2 years to flush under these conditions. See **Figure D-22**.



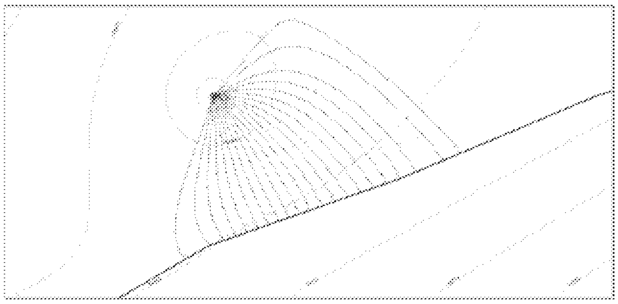


Figure D-22. GFLOW capture zone and solute breakthrough histogram for lower Animas community well. Community well (21m-174km), high pumping (Qw=817.6 m3/d) and low porosity (n=0.25). (a) capture zone delineation with 48 reverse streamlines; (b) particle tracking with 21 forward pathlines; (c) time of arrival breakthrough (days) are reported in a histogram, with a particle arriving in 94 days. Breakthrough time with same pumping but higher porosity (n=0.35) has a particle arriving in 131 days. Suggested peak river concentration is diluted to about 2% (1/48). Flushing of the aquifer in about 565 days. Note that advective transport is steady (time invariant pumping and hydrology) and does not account for dispersion, sorption, or decay of solute.

Mid Animas River Groundwater Models

A second cluster of community wells was the focus of the mid Animas River floodplain groundwater modeling (RK 65-72). The floodplain also support a large number of private/domestic wells. See **Figure D-23**.

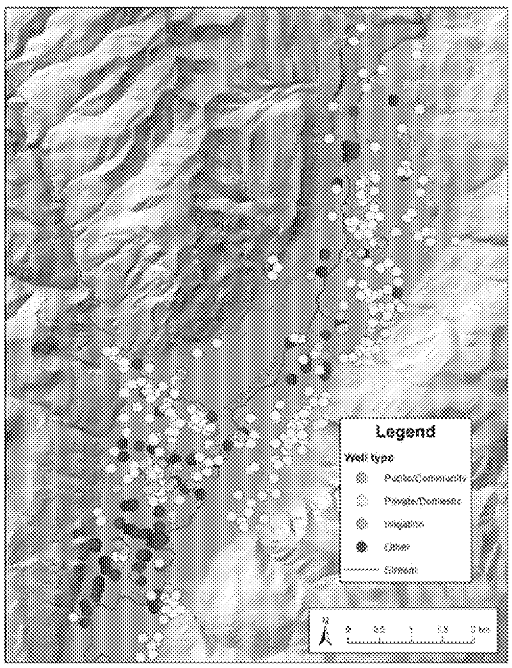


Figure 23. Water supply wells of the floodplain of the mid Animas River. The background is the topographic DEM and the hydrography of the USGS Hermosa Quad. Well data available from the Colorado DWR well permit search database. The community wells are represented by the orange circles.

Five community wells located in the mid Animas River floodplain of Colorado were nominated by EPA Region 8. The initial modeling focused on the northern cluster of wells around Hermosa, CO. The sanitation wells were not selected for modeling for it was unclear as a potential drinking water source. The straight-line distance of each community well from the river ranges from 35 m to 1000 m. The location of the nearest river shoreline was defined using the latest Google Earth imagery. The wells are about 66-72 km downstream of the Gold King Mine release point. See **Figure D-25.**

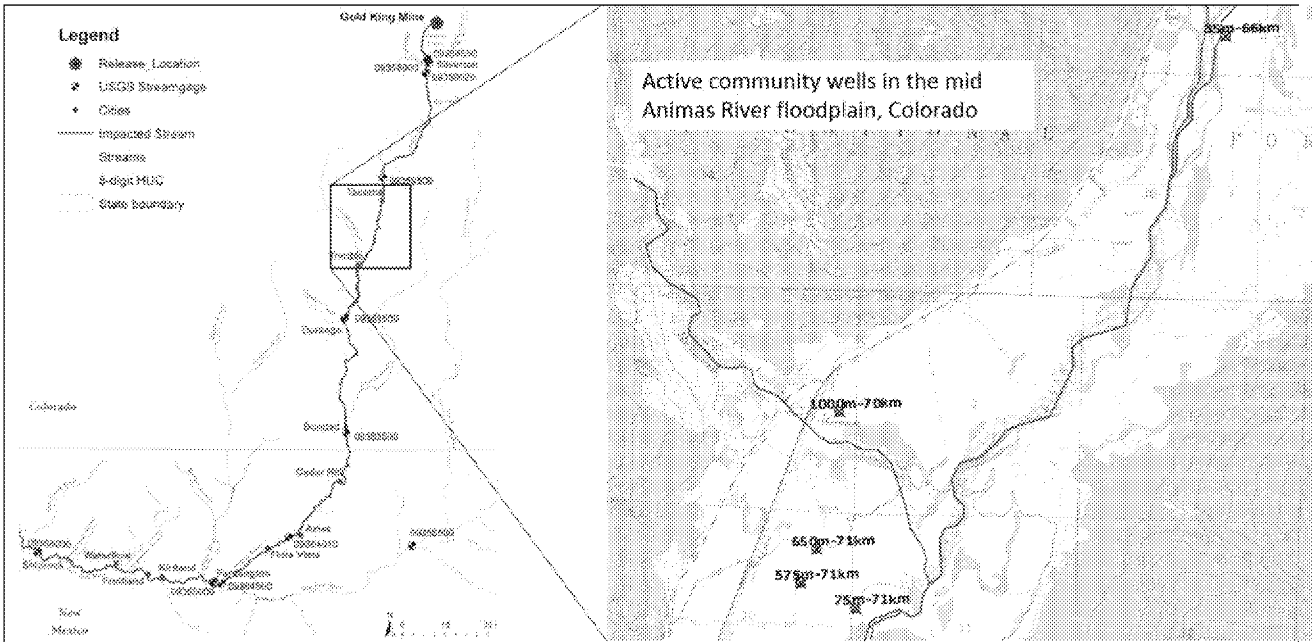


Figure D-24. Selected community wells for investigation located in the mid Animas River floodplain near Hermosa between Tacoma and Trimble, Colorado. Basemap: USGS 7.5 minute topographic DRG (digital raster graphic).

Basic information regarding the wells is reported in the Colorado Department of Water Resources Well Permit online database (www.dwr.state.co.us/WellPermitSearch). The (x, y) location of the wells are geo-referenced to electronic base maps in the UTM Zone 13 NAD83 projection and attempted confirmation with Google Earth imagery. The sustained yield and water level drawdown are reported in the driller's log. An ID was assigned to the community wells incorporating distance from river (in meters) and downstream distance from GKM (in kilometers) in the name. See **Table D-5**.

Table D-5. Community well data (source: Colorado Div Water Resources, Well Permit Search, CDNR CDSS)

Identification*	Total depth (ft)	Screened intervals (ft bgs)	Static water level (ft bgs)	Pumped water elevation (ft bgs)	Well yield (gpm) observed, estimated	Average annual well diversions (acre-ft, years)
35m66km	100	70-95	22.5	25.0	480 (580)	56.4 (1996-2014)
75m71km	87	45-85	10.5	13.5	445 (600)	145.74 (1997-2014)
575m71km	210	NA	18.2	19.3	100 (450)	139.38 (2009-2014)
650m71km	120	50-60,70-95,105-115	24	28.75	400 (600)	162.65 (1998-2014)
1000m70km	100	72.75-100	31.2	35.2	425 (425)	NA

*An ID was assigned to the community wells incorporating distance from river (in meters) and downstream distance from GKM (in kilometers) in the name.

The regional GFLOW model solves the Animas River water balance for the area draining between USGS Tall Timbers Resort, CO and the Animas River, CO for different time periods, as shown in **Table D-6**.

Table D-6. USGS streamflow data at gaging stations in mid Animas River area.

USGS Gage Name	USGS Gage Number	Discharge on 8/1/2015 (m^3/d)	Discharge averaged 2015, Aug-Oct (m^3/d)	Discharge historical, 1947-1955, Aug-Dec (m^3/d)
Animas River Tall Timbers Resort, CO	09359500	1,350,509.7	739,317.9	521,194.0
Animas River Durango, CO	09361500	1,313,811.1	898,983.6	776,518.6

The catchment between the two USGS gages of the study area and the boundary of the Animas River floodplain is defined using the USGS digital topographic map and the USGS Hermosa, CO quad geology map. **Figure D-26**.

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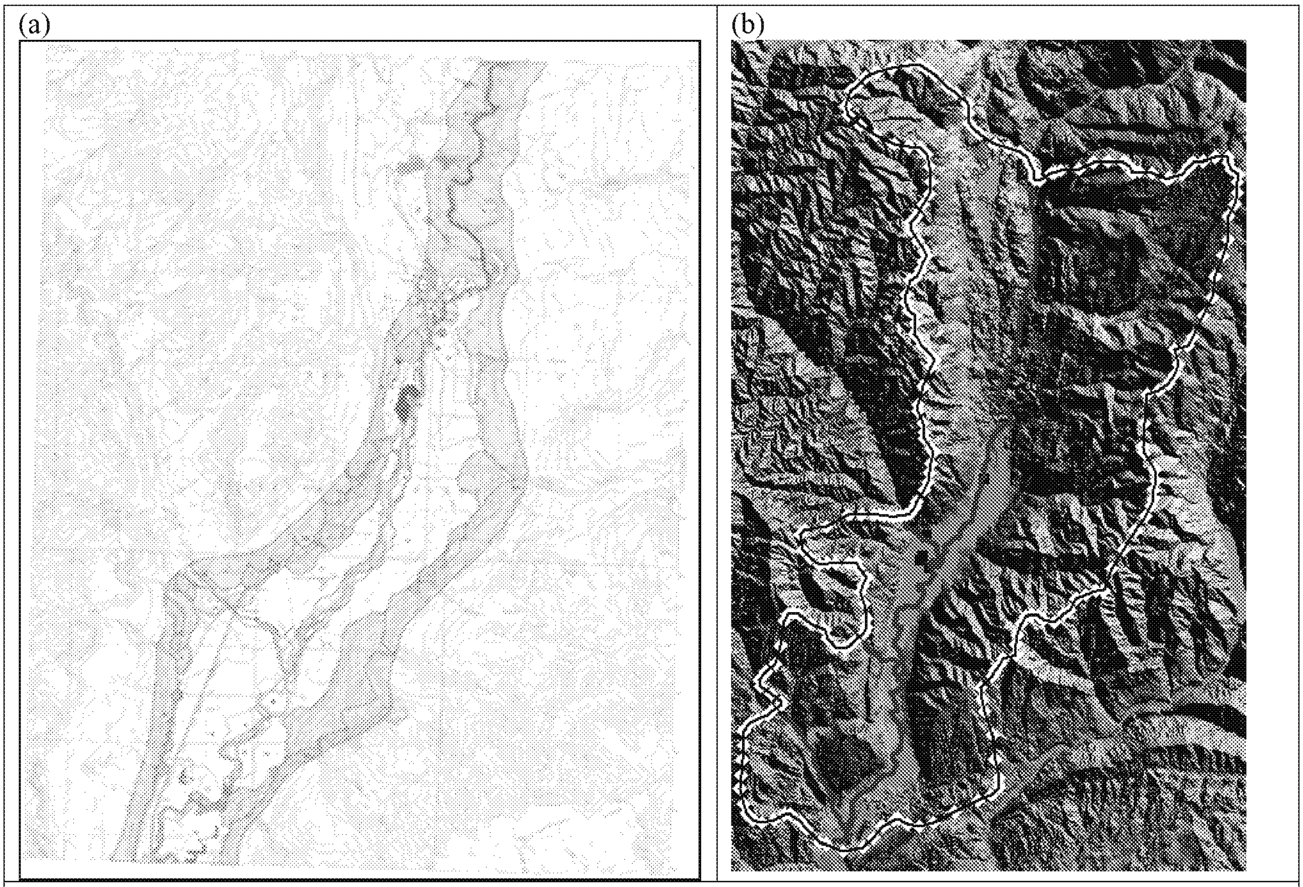

Figure D-25. Mid Animas River geology and digital elevation. (a) USGS surface geology map Hermosa, Colorado quad, showing the alluvial floodplain deposits surrounded by rock (Blair, Yager, 2002). (b) USGS NED 10m resolution and the topographically defined catchment between USGS gage stations at Tall Timbers Resort and Durango, Colorado. The alluvial floodplain shows up in light blue-green.

Mid Animas River GFLOW Model Setup

The layout of GFLOW analytic elements for the mid Animas River floodplain groundwater model is shown in **Figure D-27**. A no flow boundary is maintained at the catchment boundary or drainage area between the USGS gage on the Animas River at Tall Timbers resort, and the USGS gage on the Anims River near Duragno. The aquifer base elevation is considered no-flow in the GFLOW model. The gravimetric estimate of aquifer thickness occurred at each of the scan lines (Hasbouk Geophyiscs, Inc., 2003**; Figure D-8**). These were used to parameterize a stepping base representation in the GFLOW model.

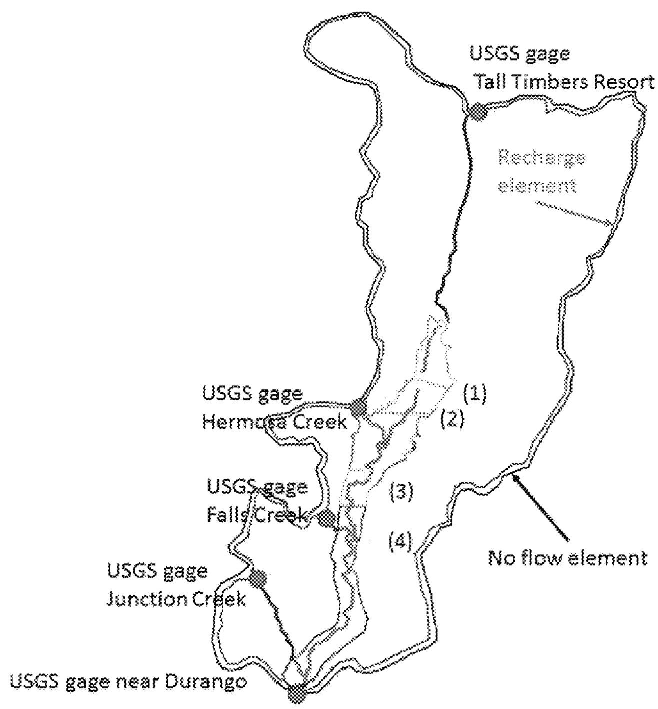

Figure D-26. GFLOW layout of analytic elements for the mid Animas River floodplain groundwater model. A no flow boundary is maintained at the catchment boundary or drainage area between the USGS gage on the Animas River at Tall Timbers resort, and the USGS gage on the Anims River near Duragno. The aquifer base elevation is considered no-flow in the GFLOW model. The gravimetric estimate of aquifer thickness occurred at each of the scan lines. These were used to parameterize a stepping base representation in the GFLOW model.

Mid Animas River GFLOW Model Calibration

Scenario 1. GFLOW model for the Aug-Dec, 1947-1955 historical time period

The Aug-Dec historical record from 1947-1955 of daily stream flows at the USGS gages at Tall Timber Resort and Durango where used to estimate the average area recharge on the catchment draining between these two stations. Model calibration for exiting average streamflows provides the estimate for average areal recharge (N = 0.000463 m/d = 6.6 in/yr). Model calibration minimizing the difference between model calculated hydraulic heads and observed water levels in wells was used to estimate hydraulic conductivity of the rocks and floodplain deposits. Unlike in the lower Animas River floodplain, we did not have the synoptic survey of water levels in wells. We used the static water levels reported in the well driller's logs. This had impact on the model error. See **Figure D-28 (a), (b), (c).**

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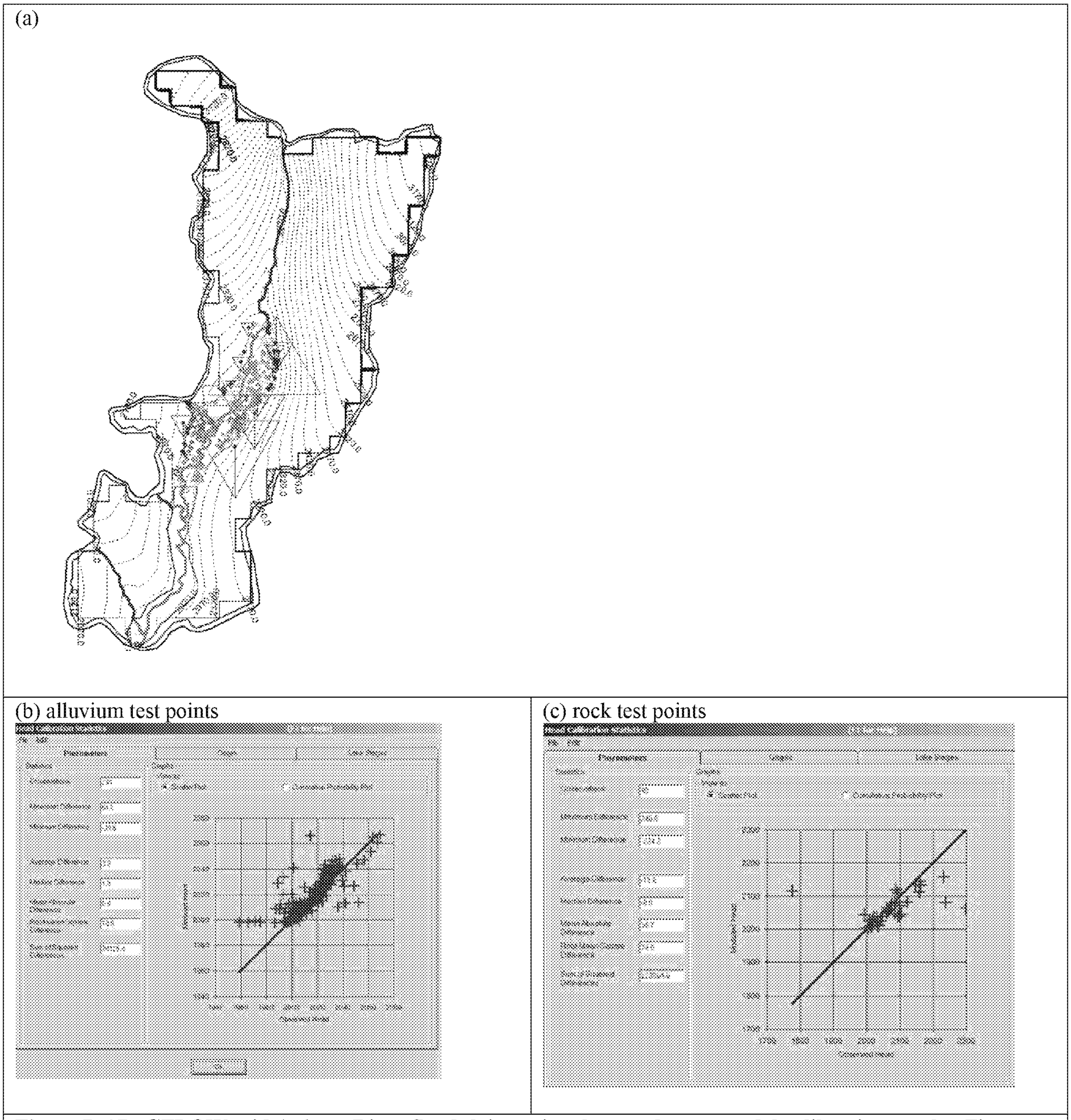


Figure D-27. GFLOW mid Animas River floodplain regional groundwater model calibration results. The model used the water balance areal recharge of N = 0.000463 m/d = 6.6 in/yr. The result of the calibration suggested the hydraulic conductivity of the rock, k_rock=0.2 m/d, and of the floodplain alluvium k_alluv = 60 m/d. (a) plot of head contours in the mid Animas River and showing test points of observed static water levels (historical). The triangles indicate the magnitude of the residual error (model – observed) and direction of triangle signifies sign of residual, positive tip of triangle up, negative tip of triangle down. (b) plot of model predicted heads vs the observed heads for the floodplain test points (avg error +3.3 m); (c) plot of model predicted heads vs the observed head for the alluvial test points (avg error -11.6m).

Scenario 2. GFLOW model for the August – October 2015 hydrologic period

Building on the previous result, the GFLOW model was adapted for the August –October 2015 mid Animas River water balance. The flow of the mid Animas River groundwater model was input at the USGS gage location at Tall Timbers resort, and the areal recharge over the study area was solved for such that the model predicted outflow in the Animas River outlet at Durango matched the observed, using data from **Table D-6**. The resulting areal recharge was N=4.377E-4 m/d.

Local scale GFLOW model for a mid Animas River floodplain community well

The GFLOW model was used to zoom into the mid Animas River floodplain near Baker's Bridge (RK 65-72) showing groundwater-surface water interactions for the averaging period August-October 2015. See **Figure D-29.**

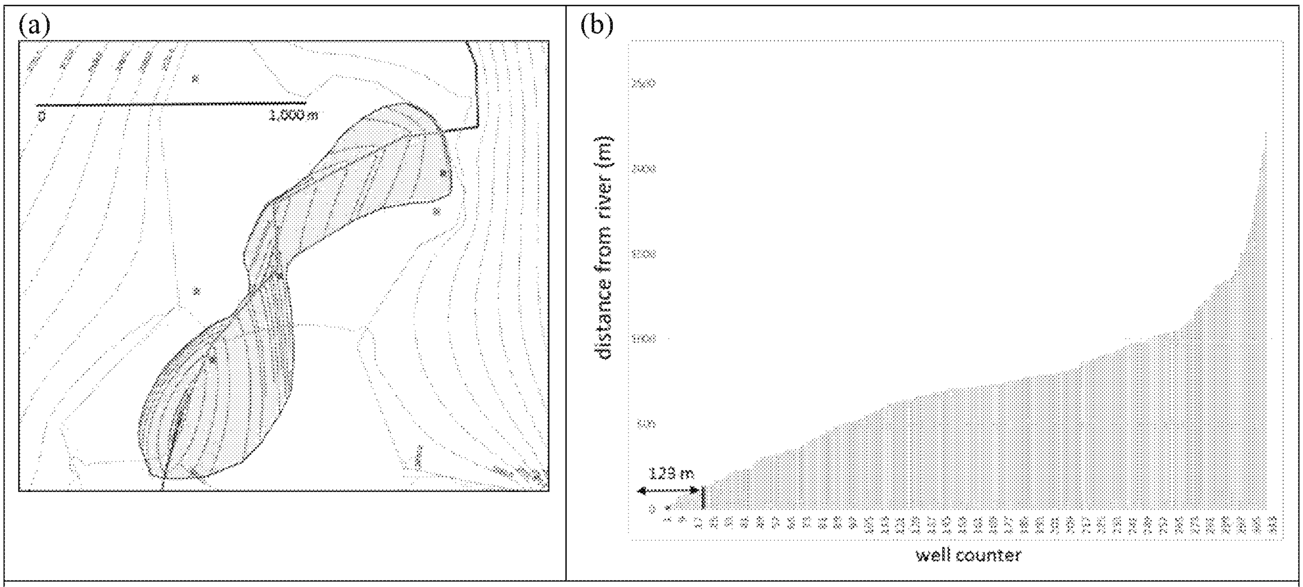


Figure D-28. GFLOW model of the mid Animas River floodplain near Baker's Bridge (RK 65-72) showing groundwater-surface water interactions for the averaging period August-October 2015. (a) Hydraulic head contours (m) are shown as dotted lines and the river flow is north to south. The gaining sections of the river are colored black; the losing sections shown in green. Forward particle traces are shown in red, with residence time limited to 90 days time-of-travel. Note there are three private domestic pumping wells located inside the "hyporheic" zone colored light red. (b) The bar graph shows the distances of wells from the river of over 300 wells. Distances ranged from 10m to over 2000 m. The GFLOW model found that only three wells (including 5 community wells) in the mid Animas River area, and distances of the wells from the river ranged from 10-123 m. There were many other wells within 123 m of the river that the model suggested do not source river water. Therefore distance from the river alone is not predictive of well sourcing from the river. Geomorphology and the location of losing sections of the river are factors. The model suggests that the Baker's Bridge area where the Animas River leaves the mountain pass and enters the floodplain valley has groundwater seeping into the aquifer and a potential "hyporheic" zone.

~~The GFLOW model predicts the community well (35m66km) would source from the Animas River under a variety of conditions. The full sensitivity analysis is presented in Appendix D. The combination of parameters (low recharge, high alluvium hydraulic conductivity, high well pumping rate, low alluvium porosity) that creates the earliest breakthrough of 25 days is shown in Figure 9-9.~~

The calibrated regional mid Animas River GFLOW model for the August – October 2015 hydro period was used to evaluate the local scale capture zones and particle tracking solute transport for the mid Animas River floodplain community well (35m66km). **Figure D-30.**

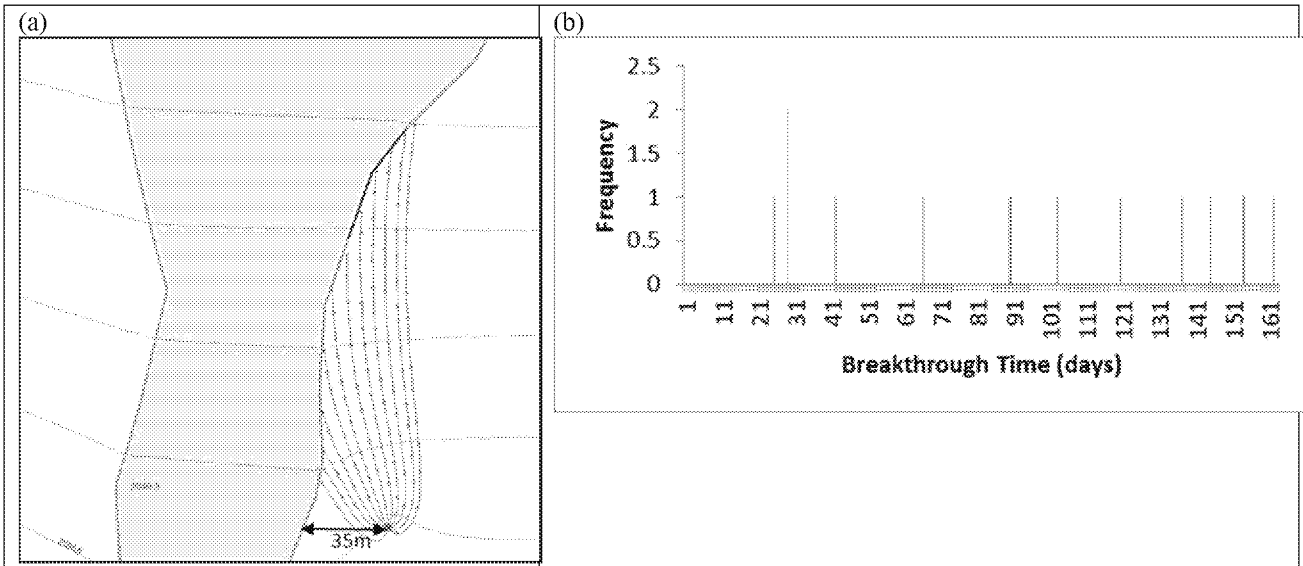


Figure D-29. GFLOW capture zone and solute breakthrough histogram for a mid Animas River community well. GFLOW analysis of mid Animas River community well (35m-66km), high pumping (Qw= 2,616.5 m3/d) and low porosity (n=0.2) (a) particle tracking with 12 forward pathlines; (b) time of arrival breakthrough (days) are reported in a histogram, with a particle arriving in 25 days. Breakthrough time with same pumping but higher porosity (n=0.35) has a particle arriving in 44 days. Suggested peak river concentration is diluted to about 17% (2/12). Flushing of the aquifer in about 160 days. Full sensitivity analysis on area recharge, hydraulic conductivity of aquifer material, and pumping rate of well is described in Appendix D. Note that advective transport is steady (time invariant pumping and hydrology) and does not account for dispersion, sorption, or decay of solute.

Consideration of Uncertainty in the Groundwater Modeling

Mid Animas: Exploration of the steady-state modeling assumption

Back of the envelope

Revisiting the issue of steady state modeling, recall **Equation (4)** for a dimensionless groundwater system response time τ:

$$\tau = \frac{SL^2}{4TP}$$

where S [-] is the aquifer storage coefficient, L [m] the distance between head specified boundaries, T [m^2/day] the aquifer transmissivity (product of aquifer thickness and hydraulic conductivity), and P [days] the period of a periodic forcing function. When considering seasonal variations in flow in an alluvial aquifer, the definition of L is more conveniently defined as the distance between the river and the valley boundary (rock outcrop). Haitjema (2006) offers the following rules of thumb:

$\tau < 0.1$ treat transient flow in the aquifer as successive steady state.

$0.1 \leq \tau \leq 1$ transient flow cannot be meaningfully represented by a steady state model.

$\tau > 1$ represent transient flow by a steady state model using average boundary conditions.

For select community wells in the mid Animas River floodplain, the calculations for τ are shown in **Table D-7**.

If the daily forcing of the community water supply wells is assumed (1 day), then > 1, independent of other properties, and steady state modeling can be applied using averaged river elevations and pumping rates. If the annual spring snow melt forcing is assumed (365 days), then there are cases where < 0.1, and successive steady state modeling can be applied, but also cases when $0.1 \leq \tau \leq 1$, and transient modeling would be required. In order to capture the full spectrum of capture zones with use of a steady state model, both actual and averaged pumping rates and river stages should encompass the full range of cases. This is explored in the sensitivity analysis presented later in the Appendix.

Table D-7. Dimensionless time factor for mid Animas River floodplain wells.

Realization	Storativity, S, (-)	Distance, L, ft	Transmissivity, T, gpd/ft	Periodicity, P, days	τ
1	0.29	2,285	314,628	365	0.02
2	0.29	2,285	129,621	365	0.06
3	0.36	2,285	129,628	365	0.07
4	0.36	2,285	129,621	365	0.07
5	0.29	4,805	314,628	365	0.11
6	0.29	5,830	314,628	365	0.16
7	0.36	5,830	314,628	365	0.20
8	0.29	4,805	129,621	365	0.26
9	0.36	4,805	129,628	365	0.33
10	0.36	4,805	129,621	365	0.33
11	0.29	5,830	129,621	365	0.39
12	0.36	5,830	129,621	365	0.48
13	0.29	2,285	314,628	1	9.00
14	0.36	2,285	314,628	1	11.17
15	0.29	2,285	129,621	1	21.84
16	0.36	2,285	129,621	1	27.12
17	0.29	4,805	314,628	1	39.80
18	0.36	4,805	314,628	1	49.40
19	0.29	5,830	314,628	1	58.58
20	0.36	5,830	314,628	1	72.73
21	0.29	4,805	129,621	1	96.59
22	0.36	4,805	129,621	1	119.91
23	0.29	5,830	129,621	1	142.20
24	0.36	5,830	129,621	1	176.52

Modeling of transient flow

The numerical model MODFLOW is capable of simulating transient flow. The community well (1000m70km, **Figure D-31**) has pumping test data to support the parameterization of the transient simulation (WestWater Associates Inc, 2010). The regional steady state GFLOW model has a MODFLOW grid extract feature to setup the initial conditions for the transient simulation. See **Figure D-32**. The GFLOW model was used to select the size of grid in that the outer boundary condition does not influence the local scale drawdowns of the pumping well. The reported data from the pumping test included 1) transmissivity equals 129,621-314,628 gpd/ft; 2) storage coefficient equals 0.006-003; and 3) specific yield equals 0.3616-0.2881. There were some complications experienced in conducting the pumping test; the ranges were reported reasonable for this type of geology.

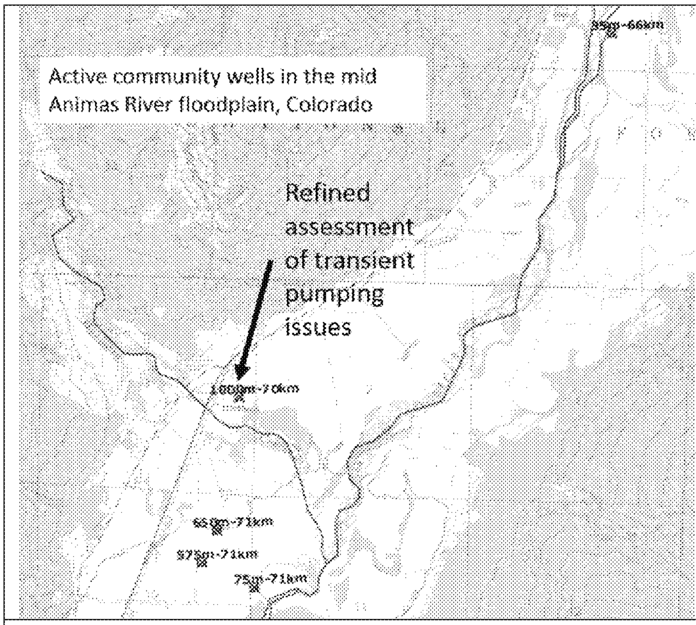


Figure D-30. The mid Animas River floodplain community well selected for exploration of transient flow. The well record included a pumping test.

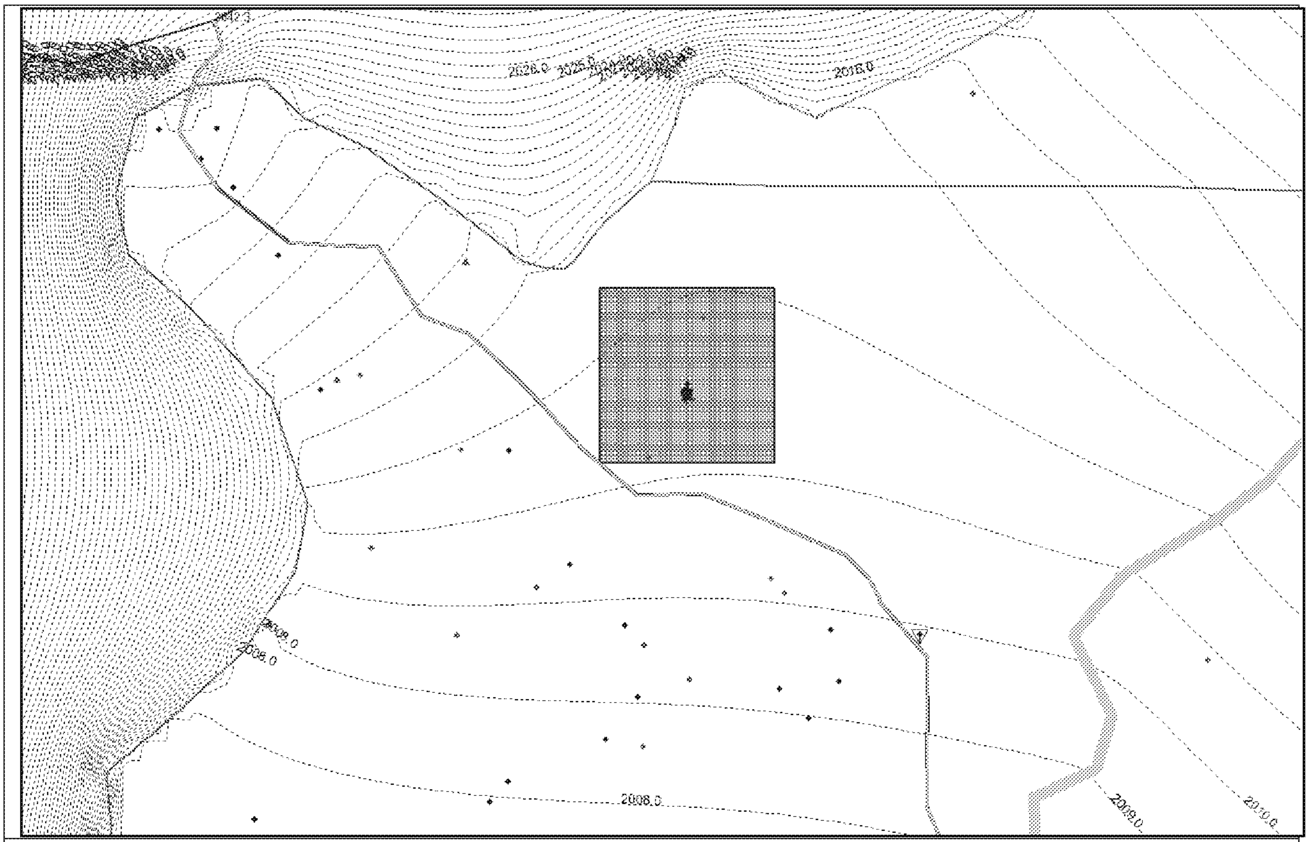


Figure D-31. The regional GFLOW model provides the initial heads to the outer cells of the MODFLOW model.

The MOFLOW model representation of the initial condition is shown in **Figure D-33**. The transient pumping well is added to this solution and placed at the center of the refined grid.

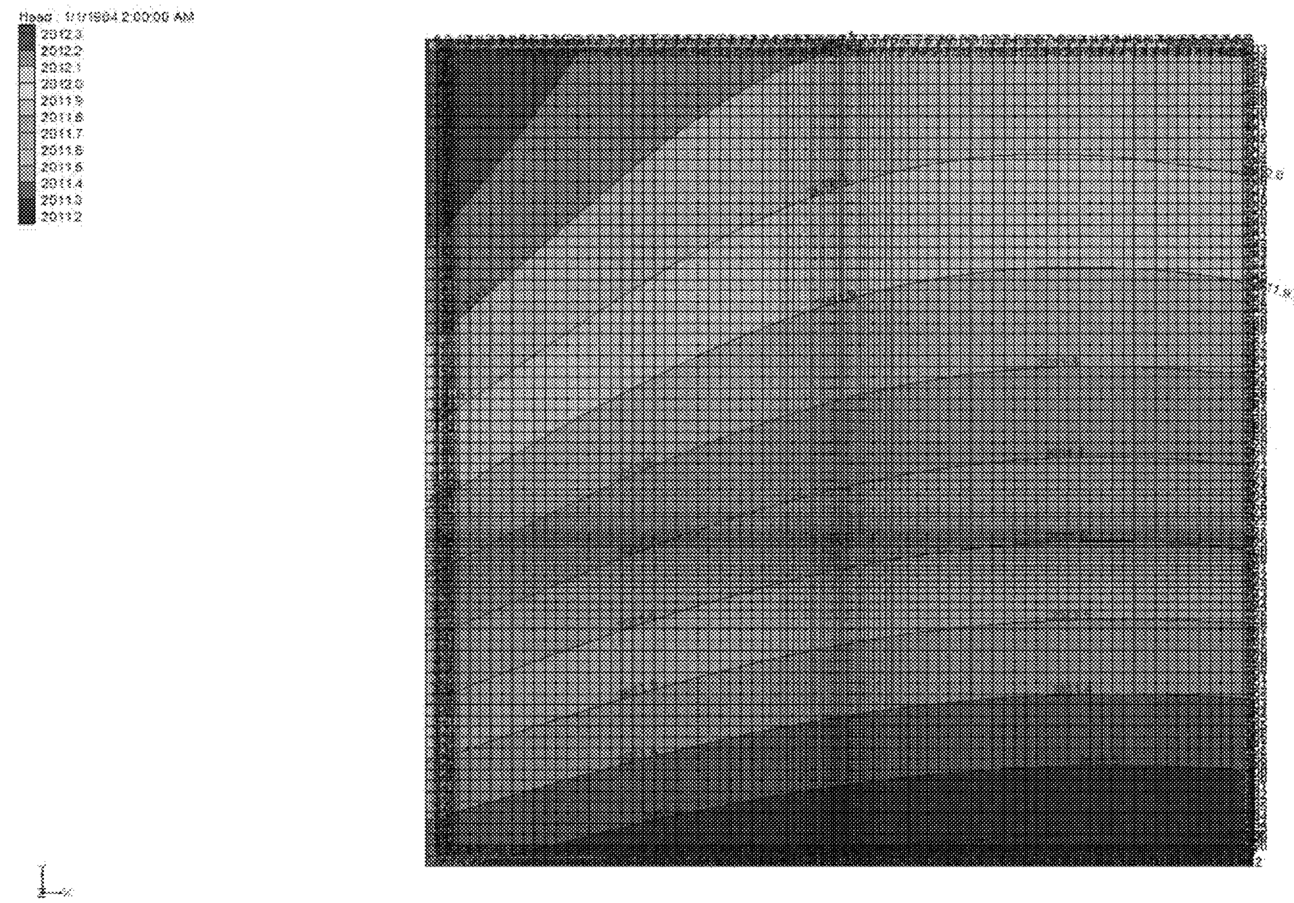


Figure D-32. The representation of initial (pre-pumping) hydraulic head conditions in the MODFLOW model.

The transient "pulsed pumping" (12 hours on daytime; 12 hours off nightime) 10-day capture zone, in comparison to the steady state solution, is somewhat bigger. See **Figure D-34**. The MODFLOW/MODPATH simulations may introduce some numerical dispersion.

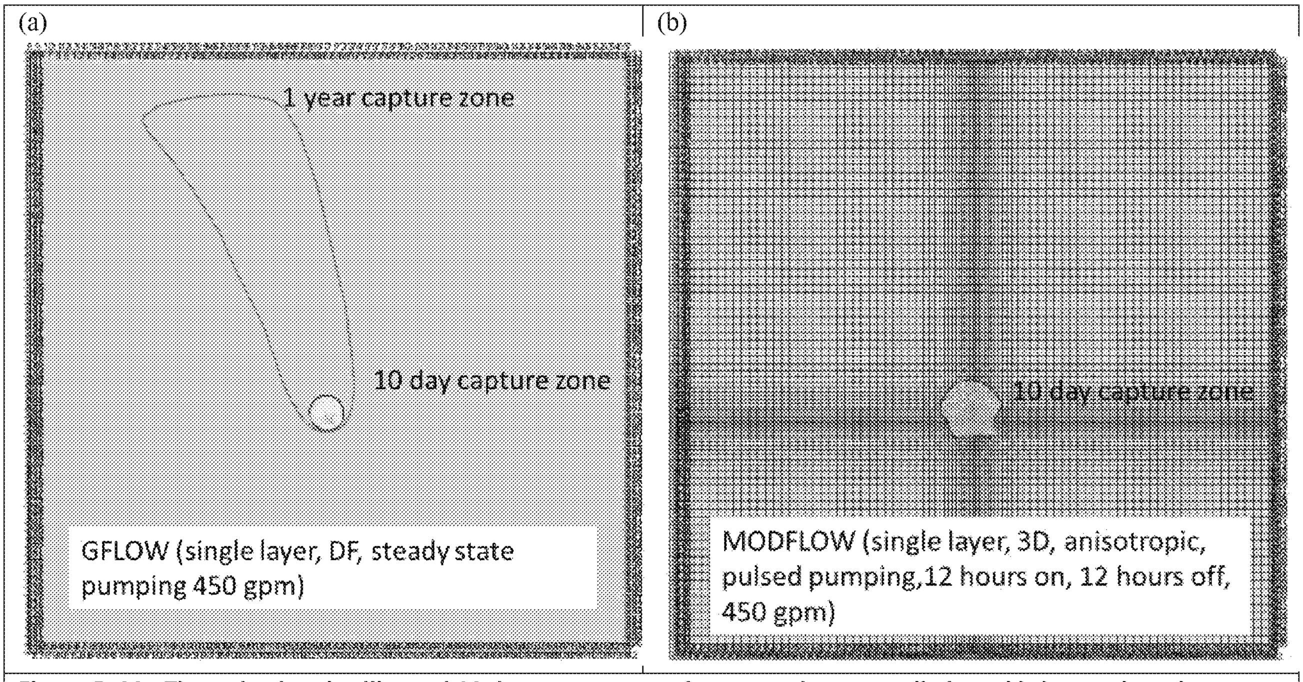


Figure D-33. The pulsed and calibrated 10 day capture zone is assumed more realistic and is larger than the steady state 10 day capture zone. Suggests there is some uncertainty in the simplified regional analysis.

Mid Animas: Exploration of fully Three-Dimensional Flow vs. Dupuit-Forchheimer Flow

The numerical model MODFLOW is capable of simulating fully 3D flow, whereas the GFLOW model simulates 3D streamlines under the Dupuit Forchheimer simplification that neglects resistance to vertical flow. The community well (35m66km, **Figure D-35**) has well driller's log data to support the parameterization of the 3D simulation (Beeman Bros. Drilling, 1984). The regional steady state GFLOW model has a MODFLOW grid extract feature to setup the initial conditions for the numerical simulation. See **Figure D-36**. The GFLOW model was used to select the size of grid in that the outer boundary condition does not influence the local scale drawdowns of the pumping well. The MOFLOW grid in plan and cross-sectional view is shown in **Figure D-37**; the location of the well is in the center of the grid refinement.

The total depth of the well is 100 feet. The 35m66km well is screened from 67 feet below ground surface to the bottom. The initial static water level was 31'10" below ground surface. The well sustained yield was 450 gallons per minute with a drawdown to 38' below ground surface.

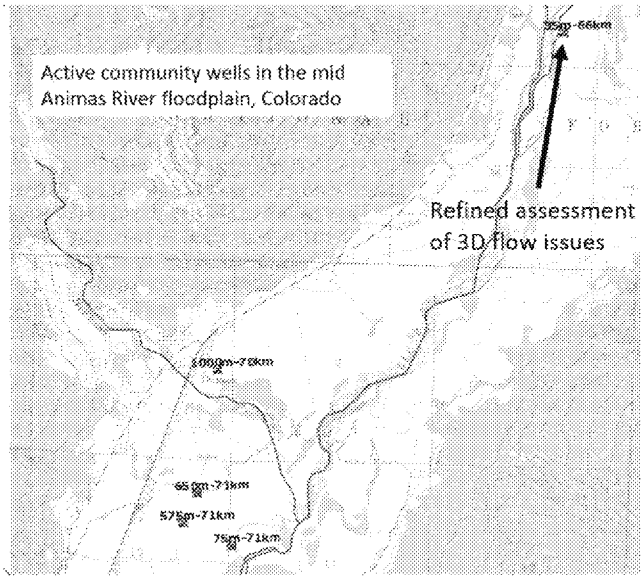


Figure D- 34. The mid Animas floodplain community well selected for three-dimensional flow assessment.

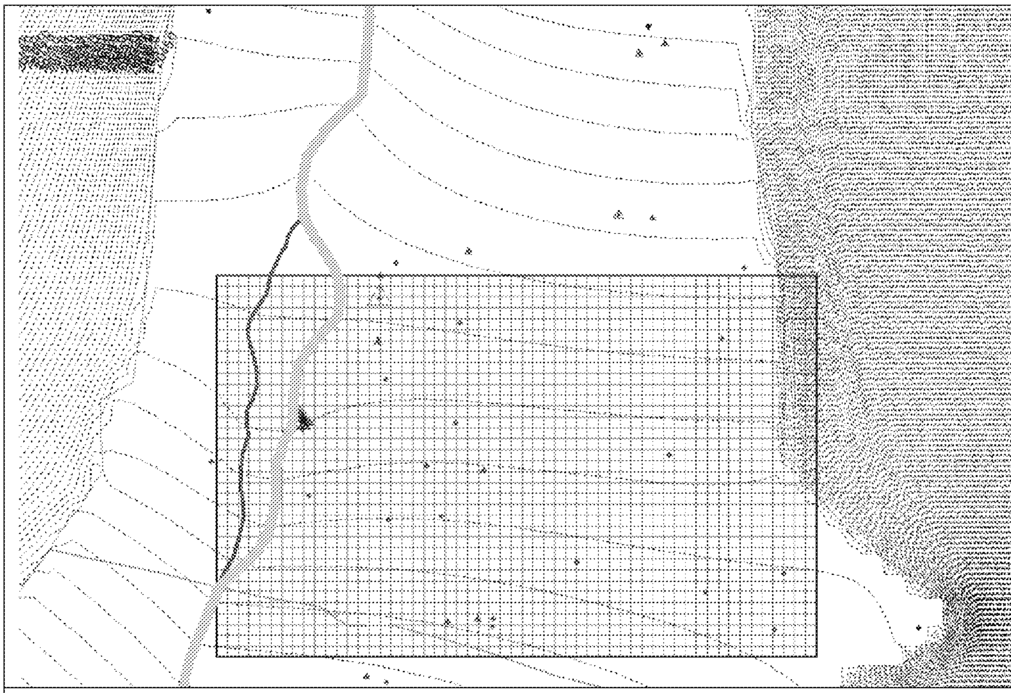


Figure D- 35. The regional GFLOW model provides the hydraulic heads for the outer cells of the MODFLOW model. The boundary of the grid extract is 1640 m by 1020 m.

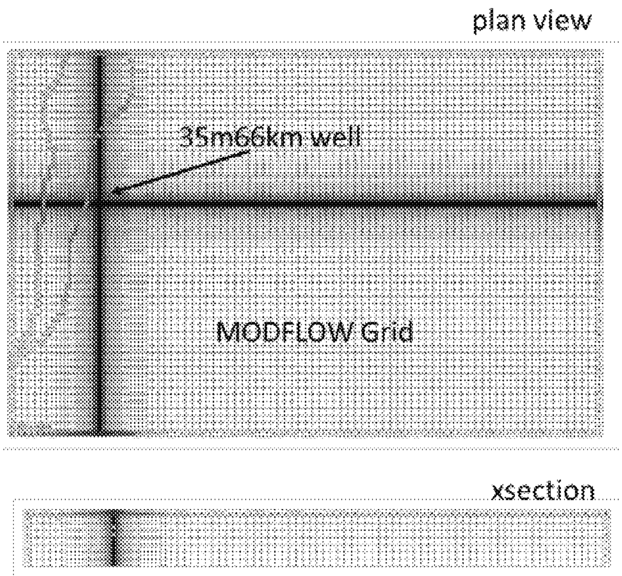


Figure D-36. The MODFLOW grid in plan view and cross-section view. The plan view cells are 1m x 1m in spatial resolution. Layers are 20 m thick.

The resulting capture zone and breakthrough times for the 3D MODFLOW simulation for mid Animas River floodplain community well (35m66km) are shown in **Figure D-38**. The well is pumping at averaged rates. The simplified GFLOW model had comparable results for the shallow capture zone associated with the top of the well screen, although MODFLOW conservative solute breakthrough was about 30 days and GFLOW breakthrough around 20 days. The MODFLOW model suggested a broader and slower forming deeper capture zone associated with the bottom well screen.

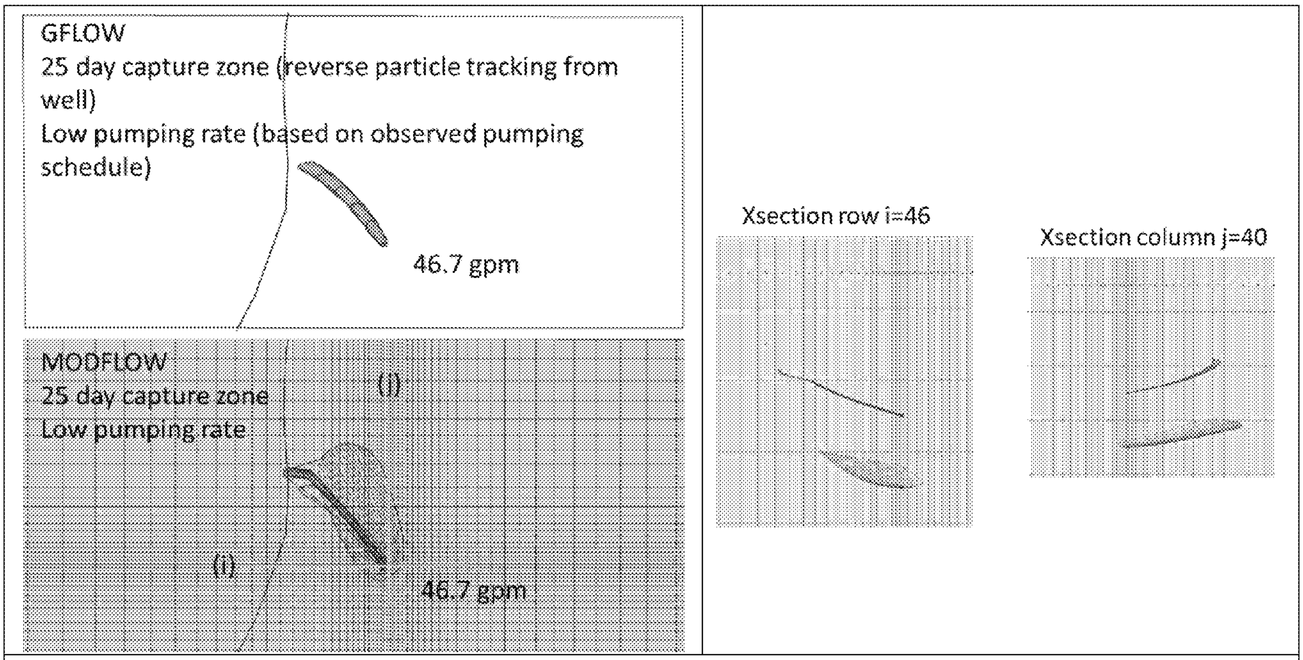
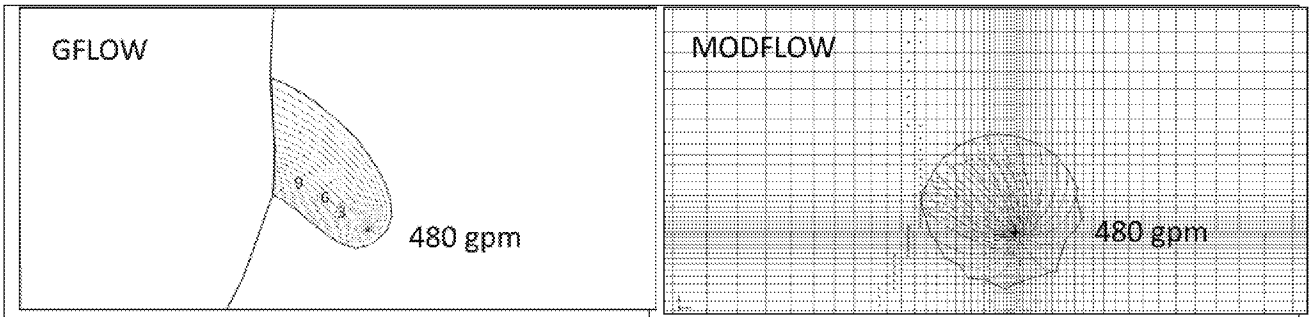


Figure D-37. The three-dimensional MODFLOW solution for the mid Animas community well. The simplified GFLOW model for well 35m66km is representative of the shallow transport pathways to the top of the well screen; the MODFLOW model shows a more complex story including different pathways to the bottom of the well screen. In both models the well communicates with the river, solute breakthrough using forward particle tracking in GFLOW is about 30 days and in MODFLOW is about 20 days.

If the well is pumped at maximum (unrealistic) rates, the simulated shallow capture zones for GFLOW and MODFLOW are closer in comparison, as shown in **Figure D-39**.



GFLOW particle breakthrough 12 days	MODPATH particle breakthrough 9 days

Figure D- 38. The influence of pumping rate on shallow breakthrough time, GFLOW in comparison to MODFLOW. Max pumping rates based on rated yield from drillers log. At the higher pumping rates, the 3D solution (MODFLOW) is closer in shape and breakthrough times to the DF solution (GFLOW). The 3D solution has earlier breakthrough times.

As expected, the simplified GFLOW model does not capture the local complexity of the MODFLOW model. The previous discussion suggested that the Dupuit-Forchheimer GFLOW model would overestimate the extent of capture. For the 35m66km well, the GFLOW model and MODFLOW model gave similar results for the shallow capture zone; MODFLOW suggested a broader and more slowly developing capture zone for the bottom of the well screen. Even with potentially longer flow pathways, the MODFLOW model predicted earlier breakthrough times. Perhaps this was a result of numerical dispersion.

Mid Animas: Sensitivity analysis of breakthrough times of a conservative solute to a pumping well

Given the uncertainties in model conceptualization and parameterization, a sensitivity analysis was conducted to better understand the influence of major factors on capture zones and breakthrough times, including areal recharge, aquifer hydraulic conductivity, and well pumping rates. The mid Animas River floodplain community well (35m66km) and the GFLOW model were used for the simulations. The summary of the runs are shown in **Table D-8**.

Table D- 8

Run	Recharge low N_{low}	Recharge high N_{high}	Hydraulic Conductivity low k_{low}	Hydraulic conductivity high k_{high}	Well pumping low Q_{low}	Well pumping high Q_{high}	Source from River?	Breakthrough (days)
1							no	NA
2							no	NA
3							yes	154
4							yes	186
5							yes	66
6							yes	109
7							yes	25
8							yes	100

N_{low}= -1.165E-4 m/d; recharge low based on 8/1/2015 water balance, negative due to evapotranspiration possibly
N_{high}=+3.915E-4 m/d; recharge high based on August-October 2015 water balance
k_{low}=8.8 m/d; hydraulic conductivity alluvium low based on transmissivity from Smith well pumping test

k_{high}=36.63 m/d; hydraulic conductivity alluvium high based on transmissivity from Smith well pumping test
Q_{low}=190.2 m^3/d; well pumping rate low based on reported diversions
Q_{high}=2616.5 m^3/d; well pumping rate high based on well driller reported yield

For this well and setting, a combination of high pumping rate, high aquifer hydraulic conductivity, and low seasonal recharge (August 2015 averaging) resulted in direct sourcing from the Animas River and the earliest dissolved solute breakthrough.

Empirical Evidence

Dissolved metals that are most useful as tracers associated with the Gold King mine plume include primarily aluminum and iron, and also manganese, zinc, and cobalt. Together these metals represent about 95% of potentially toxic metals released to the rivers (Utah DEQ, 2015). This section will visit the hypothesis that dissolved metals in the GKM river plume may have impacted floodplain wells through examination of empirical data (well water quality sampling).

Mid Animas River Floodplain Community Wells

There are interesting chemical signals of dissolved metals at the mid Animas River floodplain community well 35m66km **(Figure D-40)**. Dissolved background dissolved zinc concentrations in the upper Animas River near Elk Creek are expected to be around 0.08-0.20 mg/l as reported in Church et al (2007, Chapter E9 Quantification of metal loading by tracer injection and synoptic sampling, 1996-2000, Figure 17). The distinction between dissolved phase zinc and colloidal phase zinc in the Animas River is extensively discussed in Church et al. (1997). The observed concentration of dissolved zinc in the plume in Cement Creek was around 30 mg/l.

The observed Animas River surface water quality observations by the Colorado Department of Public Health (CDPH) at the Baker's Bridge area after the passage of the Gold King Mine plume (August 12-18) show evidence that the dissolved zinc concentrations in the river had returned to background levels of 0.09-0.13 mg/l.

The maximum observed dissolved zinc concentrations in the Animas River associated with the GKM plume near Baker's Bridge (RK 65) was about 1.7 mg/l.

The EPA WASP Animas River model gave characteristics of the dissolved zinc plume associated with the Gold King mine release moving past the 35m66km well; the plume would be expected to arrive in the area early in the day of June 6 and take less than 24 hours to pass. The CDPH groundwater quality data at the 35m66km well indicated an elevated dissolved zinc concentration of 0.58 mg/l on August 14, with lower levels observed on August 9 and August 19. Other metals showing an elevated response on August 14 included dissolved copper, lead, and nickel. See **Figure D-40**. Metals not indicating an elevated response on August 14 were aluminum, manganese, arsenic, beryllium, cobalt, selenium. pH values were not reported. Iron values were not reported.

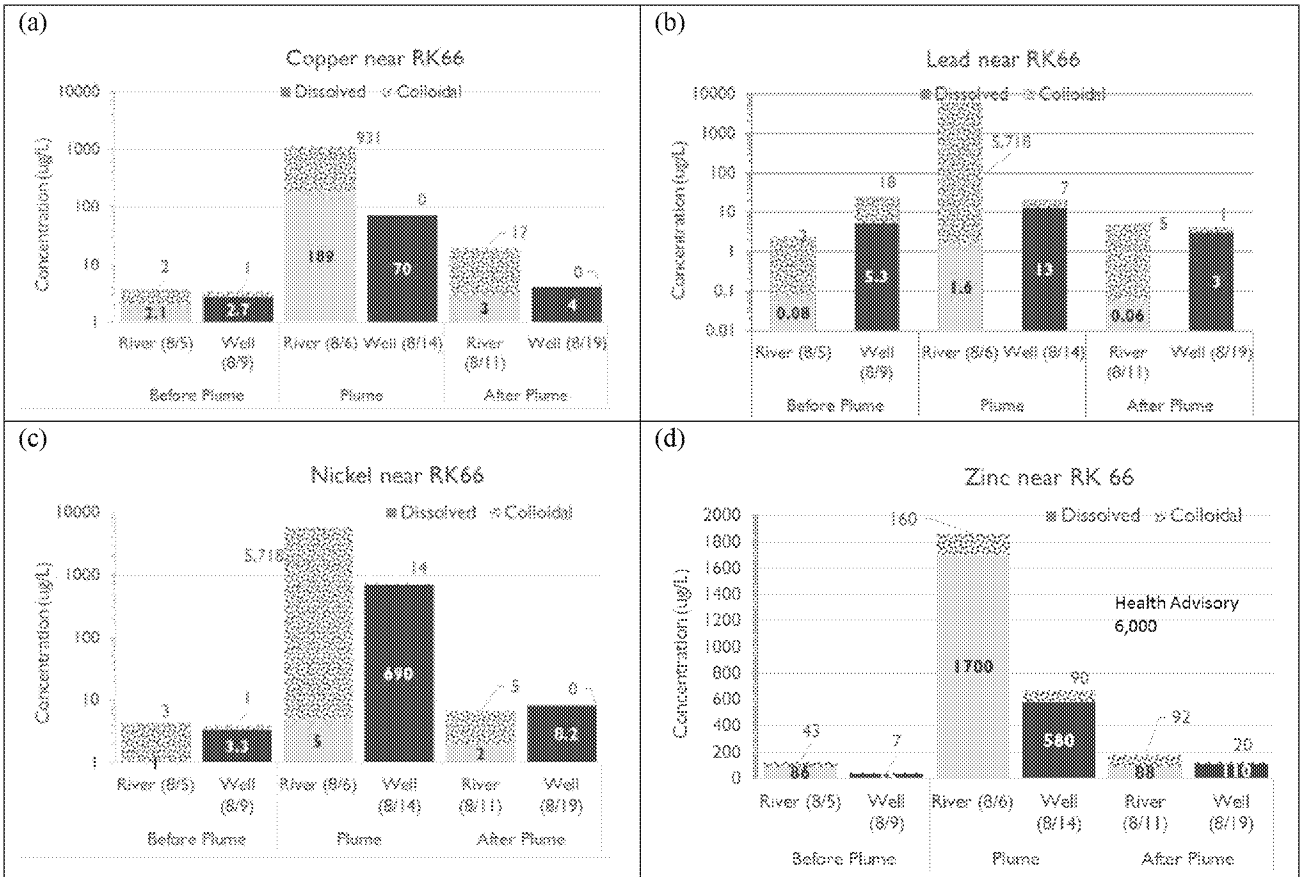


Figure D-39. River and well dissolved and colloidal metals concentrations around RK 66 of the mid Animas River in Colorado. The data is organized into before, during, and after plume time windows assuming the peak river plume passed the location on 8/6 and a potential 8 day lag in transport in the groundwater system before arrival at the well.

The CDPHE water quality measurements available in the other mid Animas community wells (75m71km, 650m71km, and 575m71km) did not have noteworthy changes suggesting impact by the acid mine drainage release.

Might the elevated dissolved zinc and other metals be indicative of Gold King Mine plume water entering the 35m66km well? The sensitivity modeling using GFLOW of solute breakthrough times ranged from 25 days to 187 days, based on choice of high or low recharge, hydraulic conductivity of the alluvium, pumping rate of the well, and aquifer porosity. The observed arrival of the dissolved zinc plume at the 35m66km community well as perhaps less than 8 days.

The groundwater modeling analysis did not include complications such as transient pumping and transient river flows, aquifer heterogeneities that might influence dissolve solute dispersion, or reactive transport that would affect metals conversions between dissolved and colloidal forms. The groundwater modeling did not include the potential for clogging of the river bed sediments by algae or precipitated chemicals. The groundwater modeling at the 35m66km well did not include potential pumping interference from nearby private wells, or the influence of irrigation ditches. The modeling did satisfy fundamental continuity of flow and fundamental physical laws of groundwater mechanics, and included the primary process of advective transport of dissolved solute.

In the end, the results of the modeling and empirical evidence cannot rule out the hypothesis that the 35m66km well did pump Animas River water impacted by the Gold King Mine release of August 5, 2015.

The significance of the potential impact is not commented on here. The secondary drinking water standard for zinc, based on taste, is 5 mg/l, and the observed peak well concentration is an order of magnitude below this standard.

Lower Animas River Floodplain Community Wells

There was no clear evidence for water quality impact of the GKM plume on the community wells sampled in the lower Animas River floodplain, between Aztec and Farmington (near RK 163. See **Figure D-41**. The dissolved metals concentrations in the lower Animas River associated with the GKM release are much lower than as observed in the mid Animas River, somewhat due to dilution and dispersion, but more likely influenced by geochemistry as segregation into colloidal form occurs. The community wells seem to indicate a fairly consistent groundwater quality concentration for cooper, lead, nickel, and zinc, perhaps indicating the aquifer waters are in a state of equilibrium or long term mixing. The active spreading of river water via irrigation ditches may be a factor.

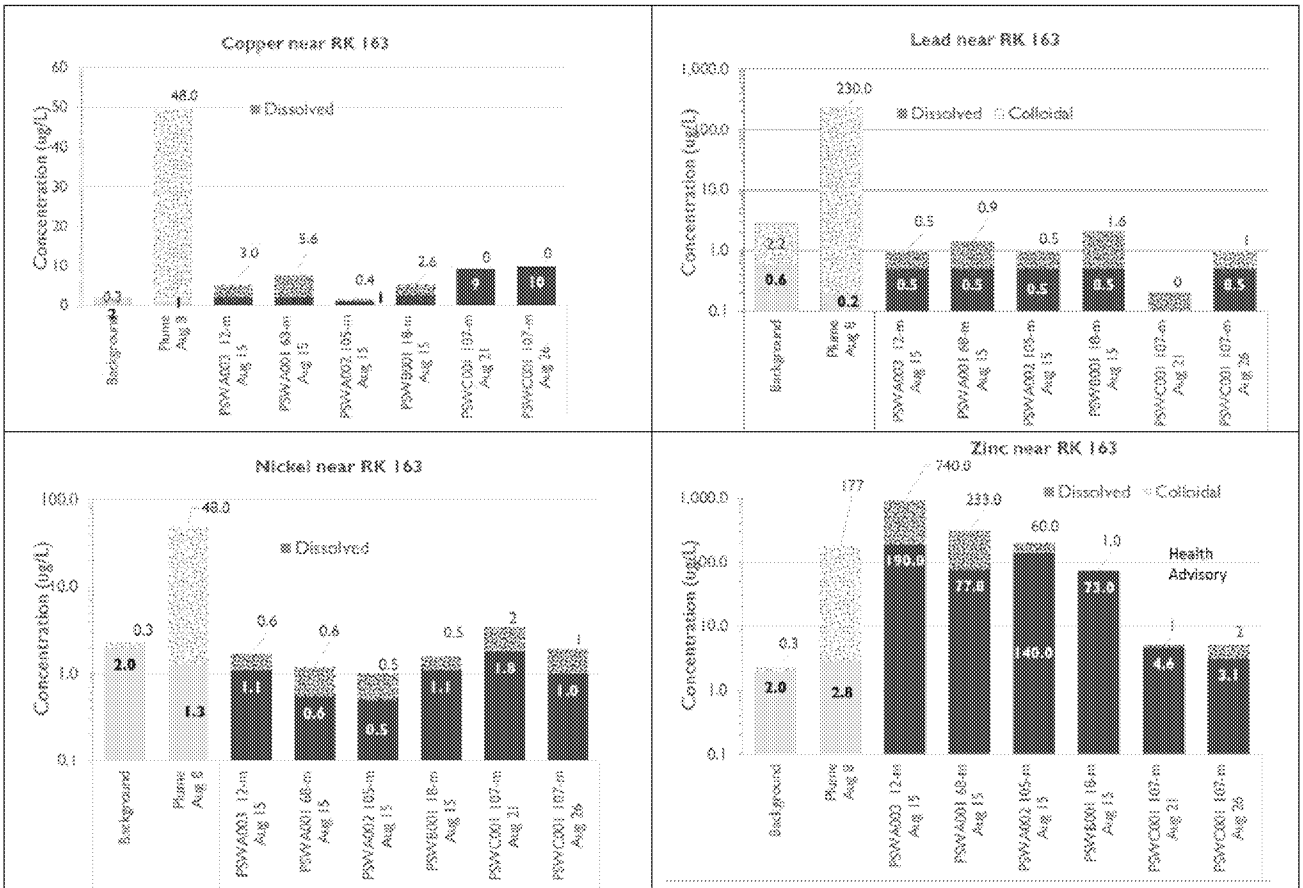


Figure D-40. River and well dissolved and colloidal metals concentrations around RK 163 of the lower Animas River in New Mexico.

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Summary

There are hundreds of water supply wells in the floodplain aquifer of the Animas River of Colorado and New Mexico, ranging from continuous larger pumping wells (the community wells) to the smaller pumpers (the domestic/household wells). There are also intermittent intermediate pumpers (the irrigation wells).

The assessment of exposure of the floodplain wells to the GKM river plume evaluated the potential for the well to source its water directly from the Animas River, and if so, the expected breakthrough time of conservative river solutes to reach the well. In addition, dilution of direct river water compared to other sources of water in the well, such as rainfall recharge or deep aquifer contributions, can be estimated.

In the Animas River floodplain, of the hundreds of domestic/household wells investigated, the groundwater modeling suggests only a handful of these wells potentially source from the Animas River and are thus vulnerable to exposure to the river plume. Given their low pumping rates, the domestic/household wells would most likely need to be located in proximity to a losing reach of the river. The complication is the nature of whether any given stretch of the Animas River is either gaining or losing is site specific and temporal. Water balance methods are too coarse to capture the dynamism; a high resolution synoptic survey of water levels during the period of plume passage would be required. The operation of nearby irrigation ditches could play a significant role in elevating water levels in the flood plain aquifers during the growing season supporting drainage toward the river.

For the community wells, because of their higher pumping rates, vulnerability to directly pumping Animas River source water would be mostly controlled by their proximity to the river. The computer modeling suggests that for the community wells located close enough to the river to directly source water (< 35 meters), there would be a delay in the GKM river plume reaching the wells (weeks to months), and significant dilution (<17% well:river).

One community well located within 35m of the Animas River in the mid valley floodplain near Baker's Bridge had a chemical signal of some dissolved metals; we could not reject the hypothesis that this signal may have been associated with the GKM plume. The observed breakthrough time was somewhat earlier than suggested by the computer simulations. The raw well water concentrations were below Federal drinking water action levels.

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